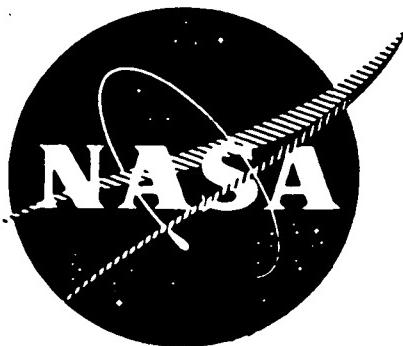


(NASA-CR-135131) DEVELOPMENT OF AN
EXTRA-HIGH STRENGTH POWDER METALLURGY
NICKEL-BASE SUPERALLOY Final Report
(Cyclops Corp., Bridgeville, Pa.) 67 p
HC A04/MF A01

N77-20208

Uncclas
CSCL 11F G3/26 22872



NASA CR-135131
U-C R-1173

DEVELOPMENT OF AN EXTRA-HIGH STRENGTH POWDER METALLURGY NICKEL-BASE SUPERALLOY

by

William B. Kent

UNIVERSAL-CYCLOPS SPECIALTY STEEL DIVISION
CYCLOPS CORPORATION

January 1977

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3-16795
Fredric H. Harf, Project Manager
Robert V. Miner, Research Advisor
Final Report

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

1. Report No. <i>NASA CR-135131</i>	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle <i>DEVELOPMENT OF AN EXTRA-HIGH STRENGTH POWDER METALLURGY NICKEL-BASE SUPERALLOY</i>		5. Report Date <i>January 1977</i>	
7. Author(s) <i>William B. Kent</i>		6. Performing Organization Code	
9. Performing Organization Name and Address <i>Universal-Cyclops Specialty Steel Division Cyclops Corporation Bridgeville, Pa. 15017</i>		8. Performing Organization Report No. <i>U-C R-1173</i>	
12. Sponsoring Agency Name and Address <i>National Aeronautics and Space Administration Washington, D.C. 20546</i>		10. Work Unit No.	
		11. Contract or Grant No. <i>NAS3-16795</i>	
		13. Type of Report and Period Covered <i>Contractor Report</i>	
		14. Sponsoring Agency Code	
15. Supplementary Notes <i>Project Manager, Fredric H. Harf, Materials and Structures Division NASA Lewis Research Center, Cleveland, Ohio</i>			
16. Abstract <i>A program was conducted to optimize the composition of NASA IIb-11, an alloy originally developed as a wrought material, for thermal stability and to determine the feasibility for producing the alloy using powder metallurgy techniques. Seven compositions were melted and atomized, hot isostatically pressed, cross rolled to disks and heat treated. Tensile and stress rupture properties from room temperature to 870°C (1600°F) were determined in addition to thermal stability characteristics. Processing variables included hot isostatic pressing parameters and handling, cross rolling procedures and heat treatment cycles. NASA IIb-11E displayed the best combination of overall properties for service as a 760°C (1400°F) disk material. Its composition is 0.06 C, 8.5 Cr, 9.0 Co, 2.0 Mo, 7.1 W, 6.6 Ta, 4.5 Al, 0.75 Ti, 0.5 V, 0.7 Hf, 0.01 B, 0.05 Zr and balance Ni. While the alloy exhibits the highest 760°C (1400°F) rupture strength reported for any powder metallurgy disk alloy to date, additional studies to further evaluate the effects of heat treatment may be required. The alloy is not susceptible to topologically close-packed phase formation during thermal exposure at 870°C (1600°F) for 1500 hours, but its mechanical property levels are lowered due to grain boundary carbide formation.</i>			
17. Key Words (Suggested by Author(s)) <i>Nickel alloys Powder Metallurgy Metallography Heat resistant alloys</i>		18. Distribution Statement <i>Unclassified - unlimited</i>	
19. Security Classif. (of this report) <i>Unclassified</i>	20. Security Classif. (of this page) <i>Unclassified</i>	21. No. of Pages <i>110</i>	22. Price* <i></i>

* For sale by the National Technical Information Service, Springfield, Virginia 22151

**Page
Intentionally
Left Blank**

FOREWORD

The work described herein was conducted over a 37 month period by the Research and Development Department of the Universal-Cyclops Specialty Steel Division, Bridgeville, Pennsylvania, under NASA Contract NAS3-16795. The contract was administered under the management of the NASA Project Manager, Mr. F. H. Harf, Materials and Structures Division, NASA Lewis Research Center. Dr. R. V. Miner served as the NASA Research Advisor.

The Project Engineer for the program was Mr. W. B. Kent of Universal-Cyclops Specialty Steel Division. Mr. L. W. Lherbier served as Program Supervisor, and technical assistance was provided by Mr. H. L. Black.

**Page
Intentionally
Left Blank**

TABLE OF CONTENTS

	<u>Page</u>
I. SUMMARY	1
II. INTRODUCTION	3
III. PROCEDURE.....	5
A. Task I - Evaluation of Alloys - Group I.....	5
1. Alloy Selection.....	5
2. Series I Evaluation.....	6
a. Materials.....	6
b. Melting and Atomization.....	6
c. Chemical Analysis.....	6
d. Processing.....	6
3. Series II - Evaluation.....	9
a. Melting and Atomization.....	9
b. Chemical Analysis.....	9
c. Processing	9
d. Heat Treatment Evaluation.....	10
e. Mechanical Testing	11
f. Thermal Stability Evaluations.....	12
g. Density Measurements.....	12
h. Data Analysis	13
B. Task II - Evaluation of Alloys - Group II.....	13
1. Alloy Selection	13
2. Melting and Atomization.....	13
3. Chemical Analysis.....	13
4. Processing	14
5. Heat Treatment Evaluation.....	15
6. Mechanical Property Evaluation.....	15
7. Thermal Stability Evaluation.....	16
8. Density Measurements.....	16
IV. RESULTS AND DISCUSSION.....	17
A. Task I - Evaluation of Alloys - Group I.....	17
1. Series I.....	17
a. Melting and Atomization.....	17
b. Chemical Analysis.....	17
c. Processing.....	17
2. Series II.....	18
a. Melting and Atomization.....	18
b. Chemical Analysis.....	18
c. Processing.....	19
d. Heat Treatment Evaluations.....	19
e. Mechanical Testing.....	21
f. Thermal Stability Evaluations.....	21
g. Density Measurements.....	22
h. Data Analysis.....	23
B. Task II - Evaluation of Alloys - Group II.....	23
1. Melting and Atomization.....	23
2. Chemical Analysis.....	23
3. Processing.....	23
4. Heat Treatment Evaluation.....	25
5. Mechanical Property Evaluation.....	26
6. Thermal Stability Evaluation.....	27
7. Density Measurements.....	28

TABLE OF CONTENTS

(continued)

	<i>Page</i>
V. <i>SUMMARY OF RESULTS.....</i>	29
VI. <i>CONCLUDING REMARKS.....</i>	30
<i>REFERENCES.....</i>	31

LIST OF TABLES

Table

- 1 *Summary of Selected Compositions for Task I and Task II Evaluations.*
- 2 *Task II HIP Handling Variables.*
- 3 *Typical Sieve Analysis For Argon Atomized Powder Heats.*
- 4 *Aim and Actual Chemical Analyses For Task I - Series I Powder Heats.*
- 5 *Task I - Series I Hot Isostatic Pressing Cycle.*
- 6 *Tramp Element and Gas Contents For Various Cross Rolled Disks.*
- 7 *Aim and Actual Chemical Analyses For Task I - Series II Powder Heats.*
- 8 *Effect of Full Solution Heat Treatment on Grain Size of Task I - Series II Alloys.*
- 9 *Results of X-Ray Phase Analyses For Task I - Series II Alloys in the Heat Treated and Heat Treated Plus Exposed Condition.*
- 10 *Tensile Properties For As-Heat Treated NASA IIb-11.*
- 11 *Tensile Properties For As-Heat Treated NASA IIb-11S.*
- 12 *Tensile Properties For As-Heat Treated NASA IIb-11A.*
- 13 *Tensile Properties For As-Heat Treated NASA IIb-11B.*
- 14 *Creep and Stress Rupture Properties For As-Heat Treated NASA IIb-11.*
- 15 *Creep and Stress Rupture Properties For As-Heat Treated NASA IIb-11S.*
- 16 *Creep and Stress Rupture Properties For As-Heat Treated NASA IIb-11A.*
- 17 *Creep and Stress Rupture Properties For As-Heat Treated NASA IIb-11B.*
- 18 *Effect of Thermal Exposure on the 760°C (1400°F) Tensile Properties of the Task I - Series II Alloys.*
- 19 *Effect of Thermal Exposure on the 760°C/620 MPa (1400°F/90 ksi) Rupture Properties of the Task I - Series II Alloys.*
- 20 *Density Measurements for the Task I - Series II Alloys.*
- 21 *Aim and Actual Chemical Analyses For Task II Powder Heats.*

LIST OF TABLES (continued)

Table

- 22 *Effect of Task II Preliminary Rolling Practices on Grain Size After Solution Heat Treatment.*
- 23 *Summary of Heat Treatment Cycles for Task II Heat Treatment Evaluation.*
- 24 *Results of Task II Heat Treatment Evaluation for NASA IIb-11C Preform C.*
- 25 *Results of Task II Heat Treatment Evaluation for NASA IIb-11C Preform C1.*
- 26 *Results of Task II Heat Treatment Evaluation for NASA IIb-11C Preform C2.*
- 27 *Results of Task II Heat Treatment Evaluation for NASA IIb-11D Preform D.*
- 28 *Results of Task II Heat Treatment Evaluation for NASA IIb-11E Preform E.*
- 29 *Results of X-Ray Phase Analyses for Task II Disks in the Heat Treated and Heat Treated Plus Exposed Condition.*
- 30 *Tensile Properties of NASA IIb-11C Disk Fabricated From HIP Preform C.*
- 31 *Tensile Properties of NASA IIb-11C Disk Fabricated From HIP Preform C1.*
- 32 *Tensile Properties of NASA IIb-11C Disk Fabricated From HIP Preform C2.*
- 33 *Tensile Properties of NASA IIb-11D Disk Fabricated From HIP Preform D.*
- 34 *Tensile Properties of NASA IIb-11E Disk Fabricated From HIP Preform E.*
- 35 *Stress Rupture Properties of NASA IIb-11C Disk Fabricated From HIP Preform C.*
- 36 *Stress Rupture Properties of NASA IIb-11C Disk Fabricated From HIP Preform C1.*

LIST OF TABLES (continued)

Table

- 37 *Stress Rupture Properties of NASA IIb-11C Disk Fabricated From HIP Preform C2.*
- 38 *Stress Rupture Properties of NASA IIb-11D Disk Fabricated From HIP Preform D.*
- 39 *Stress Rupture Properties of NASA IIb-11E Disk Fabricated From HIP Preform E.*
- 40 *Effect of Thermal Exposure on the 760°C (1400°F) Tensile Properties of the Task II Compositions.*
- 41 *Effect of Thermal Exposure on the 760°C/690 MPa (1400°F/100 ksi) Rupture Properties of the Task II Compositions.*
- 42 *Density Measurements for the Task II Compositions.*

LIST OF FIGURES

Figure

- 1 *Chart Illustrating Thermal Stability Limits Within the NASA IIB Alloy System.*
- 2 *Schematic of Canning Procedure Prior to Cross Rolling.*
- 3 *General Appearance of Task I - Series I Hot Isostatically Pressed Preforms.*
- 4 *General Appearance of Task I - Series I NASA IIB-11B Disks After Cross Rolling.*
- 5 *Scanning Electron Micrographs Illustrating Workability Failure During Cross Rolling Due to Inadequate Particle Compaction.*
- 6 *Appearance of Task I - Series II Disks After Cross Rolling.*
- 7 *Optical Micrographs Representing Task I - Series II Disks Heat Treated by Optimum Method.*
- 8 *Electron Micrographs of NASA IIB-11 in As-Heat Treated Condition.*
- 9 *Electron Micrographs of NASA IIB-11S in As-Heat Treated Condition.*
- 10 *Electron Micrographs of NASA IIB-11A in As-Heat Treated Condition.*
- 11 *Electron Micrographs of NASA IIB-11B in As-Heat Treated Condition.*
- 12 *Tensile Properties for Task I - Series II Compositions.*
- 13 *Optical Micrographs Illustrating Microstructure of Four Task I - Series II Compositions After Exposure at 870°C (1600°F) for 1500 Hours.*
- 14 *Electron Micorgraphs of NASA IIB-11 After Heat Treatment Plus Thermal Exposure.*
- 15 *Electron Micrographs of NASA IIB-11S After Heat Treatment Plus Thermal Exposure.*
- 16 *Electron Micrographs of NASA IIB-11A After Heat Treatment Plus Thermal Exposure.*
- 17 *Electron Micrographs of NASA IIB-11B After Heat Treatment Plus Thermal Exposure.*

LIST OF FIGURES (continued)

Figure

- 18 General Appearance of Task II Hot Isostatically Pressed Preforms.
- 19 Effect of Task II Preliminary Rolling Practices on Hot Workability.
- 20 General Appearance of Task II Preform Variations After Cross Rolling.
- 21 Optical Micrographs of Three Task II Compositions After Heat Treatment.
- 22 Electron Micrographs of Three Task II Compositions After Heat Treatment.
- 23 Tensile Properties For Task II Compositions.
- 24 Stress Rupture Parameter For Task II Compositions.
- 25 Optical Micrographs of Three Task II Compositions After Heat Treatment Plus Exposure at 870°C /1500 Hours.
- 26 Electron Micrographs of Three Task II Compositions After Heat Treatment Plus Exposure at 870°C /1500 Hours.

I. SUMMARY

The objective of this program was to optimize the NASA IIb-11 composition, an alloy originally developed as a conventional wrought material, and to determine the feasibility for producing the alloy using powder metallurgy techniques. The program was divided into two tasks. Task I involved a preliminary evaluation of compositions directed towards eliminating thermal instability characteristics of the wrought alloy. In Task II, further compositional and powder processing variations were evaluated.

The four Task I compositions were prepared by melting and atomization, hot isostatic pressing (HIP), cross rolling and heat treatment. Several HIP parameters were identified which can materially affect the hot workability of the HIP preforms during cross rolling. These included the degree of hot degassing, and temperature measurement and control during the HIP cycle. Results indicate a need for hot degassing at 540°C (1000°F) until nil outgassing is attained. HIP temperature/time parameters were determined to be 1245°C (2275°F) for six hours with insulated thermocouples placed directly on the load. Disks representing the Task I compositions were successfully fabricated when proper HIP parameters were employed for consolidation. Heat treatment cycles optimum for wrought material were found to be unacceptable for the powder alloys. Difficulties were encountered in obtaining the desired degree of grain boundary precipitation during aging of powder metallurgy product. As a result, none of the Task I compositions produced by powder metallurgy techniques were comparable with the mechanical properties of wrought material.

In Task II, three compositions were melted and atomized, consolidated by HIP and then processed to disks. Hot versus cold loading/unloading during HIP was found to have little effect on mechanical properties or microstructure. However, cross rolling temperature was found to have a significant effect on the response of the alloys to grain coarsening during solution treatment. A higher cross rolling temperature was found to yield coarser grain sizes than a lower temperature, especially for the low carbon compositions. Problems were experienced with excessive grain boundary precipitation during aging of the powder metallurgy product. The fine, dense carbide dispersion, typical of powder alloys, rendered solutioned carbon a ready access for grain boundary precipitation. The grain boundary carbides had an adverse effect on rupture strength. As a result, a procedure involving slow cooling from the solution treatment temperature was developed. The slow cooling permitted the carbon in solution to precipitate at higher temperatures as more stable MC carbides, and resulted in less carbon being available for precipitation during aging at lower temperatures. Significant improvements in rupture strength for all Task II compositions were observed with the slow cool heat treatment. Intermediate temperature yield strength decreased slightly. While the alloys evaluated in Task II were not susceptible to the formation of TCP (topologically close-packed) phases during an accelerated thermal exposure at 870°C (1600°F) for 1500 hours, tensile and stress rupture properties decreased

due to the decomposition of MC carbides and formation of M₆C in grain boundaries at the exposure temperature. Since the exposure temperature is well above the service temperature of 760°C (1400°F) for the alloy, one may question the validity of this "accelerated" exposure test.

II. INTRODUCTION

Since the discovery of jet engines, a continuing emphasis has been placed on increasing the thrust potential of aircraft to permit increased speeds and/or payloads. One method for achieving these increases has been through improved engine and airframe design. Considerable effort has been expended and major improvements have been achieved in these areas over the years; efforts are continuing. However, another method for increasing thrust which has not been as widely explored is the development of improved materials. If new materials could be developed which would exhibit the properties characteristics of today's materials at higher operating temperatures, the maximum engine operating temperatures could be increased and corresponding thrust improvements could be realized.

Superalloy improvements to date have primarily been achieved through increased alloy contents in nickel-base alloys. Trends toward increasing strength by precipitation hardening (gamma prime) resulted in high aluminum and titanium contents in current alloys. Also, solid solution strengthening was accomplished by increasing conventional alloying elements such as molybdenum, columbium, and tungsten. These have been supplemented by additions of more unique strengthening elements such as tantalum, vanadium, hafnium and rhenium. While the desired improvements in strength have been realized, they have carried various deficiencies with them. Among the most significant are severe segregation and poor hot workability.

Within the past several years, powder metallurgy concepts have been called upon to alleviate these deficiencies. Instead of casting large ingots of these highly-alloyed compositions with severe segregation, powder metallurgy utilizes principles of molten metal atomization to cast spherical particles less than 30 micrometers (0.010 inch) in diameter. Each particle represents the composition of the master heat; and, regardless of the complexity of the alloy, segregation effects are rendered negligible.

NASA IIb-11 represents one of the most promising experimental alloy compositions currently under development. The alloy was initially developed as a conventional wrought alloy under two NASA contracts conducted by Universal-Cyclops Specialty Steel Division, Cyclops Corporation.^(1,2) The wrought composition displayed 760°C (1400°F) strength and stress rupture properties considerably higher than any known alloy either commercially available or under development. However, the material is very difficult to hot work in the cast form such that the wrought approach may not be commercially feasible for large production quantities of the alloy. In addition, previous studies indicated the alloy was susceptible to instability after extended exposure at elevated temperatures⁽²⁾. However, this work also indicated the instability problem might be solved through minor chemistry modifications.

This program was initiated to determine the feasibility for producing NASA IIb-11 using powder metallurgy techniques. In addition, efforts

to eliminate the thermal instability of the alloy were included via modifications to the standard analysis. The program was organized to permit preliminary alloy screening studies, while establishing the feasibility for producing the alloy using a powder metallurgy approach. Secondary alloy screening and investigation of selected powder metallurgy consolidation parameters were incorporated into the final phase of the program.

III. PROCEDURE

A. Task I - Evaluation of Alloys - Group I

1. Alloy Selection

Recent development studies conducted by NASA and Universal-Cyclops on contract NAS3-14309 had shown NASA IIb-11 to exhibit the best combination of 760°C (1400°F) tensile and stress rupture properties of any currently available or developmental alloy.⁽²⁾ However, the alloy was produced using conventional cast and wrought techniques in experimental quantities. It was determined that a powder metallurgy approach would be necessary to produce production quantities of the alloy due to its high alloy content and resultant difficulty to hot work in the as-cast condition. In addition, the previous study revealed that the alloy was thermally unstable as evaluated, and recommended guidelines for improving this condition using chemistry modifications.

Guidelines for the chemistry modifications were based on a study which revealed NASA IIb-11 to be susceptible to the formation of a tungsten-rich mu-phase after long time exposure [i.e., 1500 hours at 870°C (1600°F)]. The effect of thermal exposure on the tensile properties of 17 alloy compositions within the NASA IIb alloy system is illustrated in Figure 1. This effect was determined by comparing ultimate tensile strength before and after exposure, and calculating a percent loss of ultimate strength for each composition. The compositions were subjected to electron vacancy calculations (N_v) using the method developed by Woodyatt and others.⁽³⁾ The percent loss in room temperature ultimate tensile strength versus N_v is plotted in Figure 1 for all 17 compositions. Using a ten percent loss of ultimate tensile strength as the maximum allowable loss for stable compositions, thermal stability limits within the alloy system were defined. As illustrated, compositions with N_v numbers below 2.18 would be predicted stable; the range greater than 2.18 and less than 2.22 was uncertain; and, greater than 2.22 would indicate instability.

The four alloy compositions chosen for study in Task I are listed in Table 1. The NASA IIb-11 composition developed as a cast and wrought alloy in the previous study⁽²⁾, was included as a control composition in Task I, in spite of its higher N_v number of 2.22, and its tendency towards thermal instability. Some consideration was given to the theory that the alloy might not be unstable if produced by the less segregation prone powder metallurgy techniques. The second composition, NASA IIb-11S, was modified with only slight decreases in tungsten from 7.5 to 7.0 percent, aluminum from 4.5 to 4.3 percent, and vanadium from 0.5 to 0.4 percent. These modifications were made primarily to effect a decrease in the N_v number into the predicted stable range below 2.18. Task I modifications NASA IIb-11A and IIb-11B were designed to investigate the effect of carbon and hafnium variations on the mechanical properties of NASA IIb-11. This approach was taken based on work conducted by Miner⁽⁴⁾ which was in progress.

Both a low carbon-high hafnium composition (IIb-11A) and a high carbon-high hafnium composition (IIb-11B) were formulated. Reductions in tungsten, aluminum, and vanadium were implemented at the same levels as the NASA IIb-11S composition, with the exception of NASA IIb-11A which required a further reduction in tungsten from 7.0 to 6.0 percent to maintain an acceptable N_V number. The N_V numbers for NASA IIb-11, IIb-11S, IIb-11A, and IIb-11B aim analyses were 2.22, 2.15, 2.13, and 2.14, respectively.

2. Series I Evaluation

a. Materials

Virgin raw materials were used for all heats melted to minimize the level of impurity elements and their potential effects on resultant properties. A minimum purity level of 99.9 percent was specified for all alloying elements.

b. Melting and Atomization

The four Task I compositions were vacuum induction melted in 57 kilogram (125 lb) heat quantities, and directly argon atomized into powder. The powder was collected, screened in air to -60, +325 mesh and blended.

c. Chemical Analysis

A sample for chemical analyses was taken from the vacuum induction furnace immediately prior to atomization. The samples were sectioned to provide a solid for x-ray spectrographic analysis, and lathe turned to provide chips for wet chemical analysis. Carbon, boron, hafnium, and zirconium were analyzed using wet techniques, while the balance of the elements were analyzed using x-ray spectrographic procedures.

d. Processing

(1) First Trial

(a) Hot Isostatic Pressing (HIP)

Approximately 40 kilograms (90 lb) of powder representing each of the four Task I compositions was forwarded to Battelle Memorial Institute in Columbus, Ohio for canning, evacuation, and HIP. Cylindrical containers were fabricated by Battelle to inside dimensions of 16 centimeters (6.3 in) in diameter by 15 centimeters (6.0 in) thick. The containers were prepared from 2.4 millimeter (0.095 in) thick 1008 steel. Outgassing stems of a heavier wall mild steel tubing were welded into the center of the upper lids of the containers. The container components were welded with the exception of the upper lid, and thoroughly cleaned. Powder was loaded after cleaning and lids were welded in an argon atmosphere. Approximately 18 kilograms (40 lb) of powder was loaded into each container.

The loaded containers were transferred to a heat treatment furnace and the stems were attached to a vacuum system. Prior to initiating heat, a vacuum of 0.1 Pa (1×10^{-3} mm of mercury) was attained. The containers were heated to 480°C (900°F) over a ten hour period and were held at 480°C (900°F) for one hour. The containers were cooled to 315°F (600°F) and a vacuum of 1.0 Pa (8×10^{-3} mm of mercury) was achieved prior to sealing the degassing stems. All containers were leak checked prior to initiating the HIP cycle.

The containers were loaded by stacking into the autoclave and unshielded thermocouples were placed at the top and bottom container in the vessel (T/C-1 and T/C-2). Thermocouples were also placed 90° from the above thermocouples at the mid-point of the load and 15 centimeters (6 in) below the load; these were designated T/C-5 and T/C-6, respectively. Pressing was accomplished by subjecting the load to maximum temperature/pressure parameters of 1150°C (2100°F) and 100 MPa (15 ksi) for three hours.

(b) Cross Rolling

The HIP preforms consolidated at Battelle were prepared for cross rolling by machining, sectioning and recanning. The HIP cans were removed by lathe turning, as was a slightly porous surface layer; previous experience has indicated workability problems can result if this layer is not removed prior to subsequent hot working. After turning the outside diameter, the billets were each sectioned in half and all faces were turned parallel. The dimensions of all eight preforms prior to canning were 13 centimeters (5 in) in diameter by 6 centimeters (2.375 in) thick. The preforms were placed into sections of mild steel tubing cut to the same thickness with an inside diameter of 13 centimeters (5 in) and a wall thickness of 2.5 centimeters (1.0 in). Cover plates of UT HX, a nickel base solid solution hardened alloy, were TIG welded to the mild steel as shown in Figure 2 using UT HX filler wire.

The eight canned preforms were forwarded to Universal-Cyclops' Pittsburgh Plant for cross rolling. The preforms were soaked at 1065°C (1950°F) for four hours prior to rolling. Rolling was conducted using ten single passes with reheating at 1065°C (1950°F) after each pass. Rolling reductions were initiated with light five percent passes and reductions were gradually increased to ten percent. The actual ten pass sequence was five, five, seven, seven, nine, nine, nine, nine, ten and ten percent. The cans were indexed 90° after each pass to maintain the circular configuration of the preforms. The total material reduction was 56.7 percent from 6 centimeters (2.375 in) thick to 2.6 centimeters (1.028 in) thick.

(c) Evaluations

After cross rolling, the eight canned preforms were decanned and seven of the eight disks revealed severe cracking. The poor workability experience necessitated additional evaluations to determine the

cause for the severe cracking. Samples representing the two NASA IIb-11B disks were analyzed for argon, hydrogen, oxygen and nitrogen. Although these disks were sectioned from the same preform, one cracked severely while the other displayed no cracking. In addition, material representing each of the four alloy compositions was analyzed for tramp elements including manganese, silicon, sulfur and phosphorus. The possibility of trace element contamination was also explored with a sample of NASA IIb-11 submitted for analysis by mass spectrographic techniques for nearly 70 elements. Finally, samples of the fractured areas were examined using a scanning electron microscope (SEM).

(2) Second Trial

(a) Hot Isostatic Pressing

Using remaining powder available from initial melting and atomization, additional HIP trials were conducted at Industrial Materials Technology (IMT) in Woburn, Massachusetts. Approximately 6.8 kilograms (15 lb) of powder representing each of the four compositions was canned in one master can. A section of 6.4 millimeter (0.25 in) wall tubing approximately 30.5 centimeters (12 in) high with an 18 centimeter (7 in) inside diameter was used. Mild steel spacers 1.25 centimeters (0.5 in) thick were used as tops and bottoms and to separate the four compositions. The spacers were 16.5 centimeters (6.5 in) in diameter, and mild steel powder was used to fill the annular ring between the outside diameter of the spacers and the can wall. The container was pumped cold to a vacuum of 0.001 Pa (1×10^{-5} mm) and heated slowly to 650°C (1200°F), maintaining high vacuum. The can was held until no outgassing was observed, which in this case was 24 hours. After sealing, the can was placed in an autoclave and subjected to maximum HIP parameters of 1200°C (2200°F) and 103 MPa (15 ksi) using a three hour hold at maximum conditions. The control thermocouple was placed at the top of the can and was insulated and shielded using refractory grouting.

(b) Cross Rolling

The HIP preform resulting from the IMT cycle was sectioned, machined and recanned in preparation for cross-rolling. Sufficient material was removed to insure no contamination from the mild steel separators or powder. The pieces were machined to sizes of 13 centimeters (5.2 in) diameter by 3.8 centimeters (1.5 in) thick prior to canning. Canning was conducted following procedures described in the previous section. Cross rolling was also conducted according to temperatures and reduction percentages outlined in a previous section. Again, the total material reduction was 56.7 percent.

(c) Evaluations

After cross rolling, the four disks were decanned. The pieces were cracked so severely that testing could not be performed.

3. Series II - Evaluation

a. Melting and Atomization

The four Task I compositions were remelted to provide powder for a repeat of the Task I trials. The compositions were melted and atomized in 45 kilogram (100 lb) heat quantities. The powder was collected, screened in air to -60, +325 mesh and blended.

b. Chemical Analysis

The sample for chemical analysis was taken from the vacuum induction furnace immediately prior to atomization. Analytical techniques were as previously described.

c. Processing

(1) Hot Isostatic Pressing

Material representing each of the four compositions was loaded into cans with inside dimensions of approximately 16.5 centimeters (6.5 in) diameter by 13 centimeters (5 in) thick. The containers were fabricated by IMT. The cans were hot degassed as previously described at 650°C (1200°F) and then subjected to HIP at maximum temperature/pressure parameters of 1230°C (2250°F) and 103 MPa (15 ksi). The hold time at maximum conditions was six hours.

(2) Cross Rolling

The Series II HIP preforms consolidated at IMT were sectioned and machined in preparation for cross rolling. Two pieces were prepared representing each composition with approximate dimensions of 13.8 centimeters (5.45 in) in diameter by 4.5 centimeters (1.75 in) thick. Canning was conducted as described previously, and illustrated in Figure 2. The eight preforms were rolled from 1065°C (1950°F) using the same pre-heating time and reduction sequence as described previously. The ten single passes resulted in a total material reduction of 56.7 percent.

(3) Structural Examinations

After cross rolling, one preform representing each composition was sectioned to provide micro samples from edge, mid-radius and center locations. Samples for light microscopy were mounted, polished and etched using one or more of the following etches to provide the desired structural features:

- (a) 60 percent water
- 15 percent sulfuric acid
- 15 percent hydrofluoric acid
- 9 percent nitric acid
- 1 percent hydrogen peroxide

- (b) 85 percent water
14 percent hydrochloric acid
1 percent hydrogen peroxide
- (c) 33 percent nitric acid
33 percent acetic acid
33 percent citric acid
1 percent hydrofluoric acid

d. Heat Treatment Evaluation

(1) Selection of Optimum Treatment

The optimum heat treatment determined for the wrought version of NASA IIb-11 was as follows: 1220°C (2225°F)/2 hours/RAC + 870°C (1600°F)/16 hours/RAC + 760°C (1400°F)/16 hours/AC⁽²⁾. This represents a three stage heat treatment involving full solution treatment, intermediate aging and final aging, respectively. Rapid air cooling (RAC) was accomplished by forced air blower. Using the above as a guideline, the objective of this evaluation was to determine the optimum heat treatment for powder NASA IIb-11 variations. Thirteen samples were sectioned from disks representing each of the four compositions. Eight full solution heat treatment variations involving temperature and time were evaluated for each composition as follows:

Full Solution Treatments (FST)

- [1] 1220°C (2225°F)/2 hours/RAC
- [2] 1220°C (2225°F)/60 hours/RAC
- [3] 1230°C (2250°F)/2 hours/RAC
- [4] 1230°C (2250°F)/4 hours/RAC
- [5] 1230°C (2250°F)/24 hours/RAC
- [6] 1245°C (2275°F)/2 hours/RAC
- [7] 1260°C (2300°F)/2 hours/RAC
- [8] 1260°C (2300°F)/6 hours/RAC

Based on examination by optical microscopy, an optimum full solution treatment was to be chosen for each composition based primarily on achieving a grain size in the desired range of ASTM 4 to 5.

Four intermediate aging variations involving temperature and time were also evaluated in combination with the chosen optimum full solution treatment for each composition as follows:

Intermediate Aging Treatments (IA)

- [1] FST + 870°C (1600°F)/16 hours/RAC
- [2] FST + 900°C (1650°F)/16 hours/RAC
- [3] FST + 1040°C (1900°F)/2 hours/RAC
- [4] FST + 1065°C (1950°F)/2 hours/RAC

Based on optical microscopy examination, an optimum intermediate aging treatment was selected for each composition based on an arbitrarily desired degree of gamma prime and grain boundary carbide precipitation.

Prior studies had conclusively shown that a final aging treatment of 760°C (1400°F)/16 hours/AC was optimum and this treatment was employed for each composition after the optimum full solution and intermediate aging treatments had been selected.

(2) Structural Examinations

All thirteen heat treatment variations for each composition were characterized by optical microscopy examination. In addition, electron microscopy and x-ray phase analysis were used to further characterize the fully heat treated samples from each composition. Samples were prepared for electron microscopy by mechanically polishing through 600 grit silicon carbide abrasives, followed by electrolytic polishing in a solution of perchloric acid in alcohol. A variety of etching solutions similar to those described in a previous section were employed to accentuate the desired structural characteristics. The polished and etched specimens were single-stage replicated using a one percent solution of parlodion in isoamylacetate. Shadowing was performed with chromium at various angles of deposition. Photographs were taken at various magnifications; however, all were photographically enlarged to twice the indicated microscope magnification (i.e., 3000X to 6000X).

As-heat treated samples were prepared for x-ray analysis by machining to a standard size, electrolytically cleaning in a ten percent solution of hydrochloric acid in methanol for ten minutes, rinsing, and electrolytically digesting in a solution of the same mixture for 30 minutes at a current density of approximately 0.04 A/cm^2 (0.25 A/in^2). This extraction procedure is designed to dissolve the matrix selectively while permitting intermetallic phases to remain unattacked and collect in the bottom of the container. The extracted residues were cleaned in methanol, dried, mounted on glass slides and subjected to x-ray diffraction analysis. The resulting patterns were compared with standard ASTM reference cards to identify phases present.

e. Mechanical Testing

Specimens for mechanical testing were sectioned from each of the disks by abrasive cutting, rough machining, heat treating, and finish machining and polishing to the prescribed dimensions. All specimens conformed to ASTM specifications.

(1) Tensile Tests

Tensile tests were performed in duplicate on material representing each composition at room temperature, 650°C (1200°F), 760°C (1400°F) and 870°C (1600°F). All tests were conducted on a 225 kilonewton (50,000 pound) unit. The specimens were pulled at a nominal strain rate of $0.005 \text{ minute}^{-1}$ up to the yield point, where the rate was increased to 0.05 minute^{-1} . The 0.2 percent yield point was measured using a deflectometer.

(2) Stress Rupture Tests

Duplicate stress rupture tests were conducted for each composition at three conditions including 650°C/1210 MPa (1200°F/175 ksi), 760°C/620 MPa (1400°F/90 ksi) and 870°C/380 MPa (1600°F/55 ksi). All tests were conducted on lever arm testing machines with furnaces controlled to $\pm 3^\circ\text{C}$ (5°F). Rupture life was measured from the time of application of the load (approximately 15 minutes after temperature equalization).

(3) Creep Tests

Duplicate creep tests were conducted on material representing each composition at conditions of 760°C/620 MPa (1400°F/90 ksi). Furnace and loading conditions were as described above for stress rupture tests. The time to 0.2 percent creep was measured using an extensometer.

f. Thermal Stability Evaluations

(1) Thermal Cycle

Specimens representing each of the four Task I - Series II compositions heat treated per experimentally determined results were exposed for 1500 hours at 870°C (1600°F). These specimens included two tensile and two stress rupture blanks along with samples for structural examination. All material was enclosed in a protective package during the exposure to prevent excessive oxidation or external contamination.

(2) Mechanical Testing

After exposure at 870°C (1600°F), the tensile and stress rupture specimen blanks were finish machined and polished to size. Duplicate specimens were tested in tension at 760°C (1400°F) and in stress rupture at 760°C/620 MPa (1400°F/90 ksi). Direct comparison with as-heat treated results established the effect of the exposure on these property characteristics.

(3) Structural Examinations

Samples from each composition after exposure were examined using optical and electron microscopy and x-ray phase analysis procedures as described in a previous section. Again, direct comparison with as-heat treated specimens established the effect of the exposure on structural characteristics.

g. Density Measurements

As-rolled specimens representing each of the four Series II compositions were subjected to density measurement using water displacement procedures.

h. Data Analysis

Prior to proceeding into Task II of the contract, Task I mechanical property data and structural examinations were reviewed in detail with the objective of selecting one of the Task I compositions for more detailed study in Task II. However, since results for the best Task I alloy were not favorable as compared with the originally developed wrought version of the alloy, additional compositional screening studies were performed in Task II.

B. Task II - Evaluation of Alloys - Group II

1. Alloy Selection

Chemistry modifications for Task II alloys were formulated based on Task I results combined with input from previous programs.^(2,4) Due to problems in achieving adequate grain growth in the Task I compositions, lower carbon levels of 0.055 and 0.095 percent were selected for Task II compositions. Hafnium was also evaluated at levels of 0.7 and 1.3 percent, which permitted evaluation of interactions: high carbon-high hafnium, low carbon-high hafnium, and low carbon-low hafnium. Several other chemistry modifications common to Task II alloys were made to maintain N_V numbers below the 2.18 limit. Due to the decreased availability of carbon compared with the base Task I composition, carbide forming elements such as tantalum and tungsten were reduced from 7.0 to 6.6 percent and from 7.5 to 7.1 percent, respectively. In addition, chromium was reduced from 9.0 to 8.5 percent, also in the interest of maintaining low N_V levels. Aluminum and vanadium were raised slightly to levels of the original NASA IIb-11 composition. The three Task II alloys were also melted to lower boron and zirconium levels than the original composition. Boron was lowered from 0.02 to 0.01 and zirconium from 0.1 to 0.05 percent; original levels were believed too high for alloys of this type. The N_V numbers for the Task II alloys identified as IIb-11C, IIb-11D and IIb-11E were 2.14, 2.16 and 2.13, respectively. The compositions formulated for evaluation in Task II of this program are listed in Table 1 along with the Task I compositions.

2. Melting and Atomization

The three Task II alloys were melted and atomized to powder using procedures previously described for the Task I materials. NASA IIb-11C was melted as one 90 kilogram (200 lb) heat while alloys IIb-11D and IIb-11E were each melted as 35 kilogram (75 lb) heats.

3. Chemical Analysis

Solid specimens for chemical analysis were taken representing each heat immediately prior to atomization. Analysis techniques were as previously described.

4. Processing

a. Hot Isostatic Pressing

A total of five cans, three representing IIb-11C and one each representing IIb-11D and IIb-11E, were prepared for hot isostatic pressing. All canning, evaluation and pressing was conducted by Federal-Mogul Corporation, Detroit, Michigan. The can inside dimensions were approximately 15 centimeters (6 in) in diameter by 15 centimeters (6 in) high. The powders were loaded into the cans, evacuated by heating to 425°C (800°F) until desired vacuum levels and leak rates were achieved, then sealed. One can representing each of the three compositions was subjected to pretreatment at 980°C (1800°F), loaded hot into the autoclave, and pressed at conditions of 1245°C (2275°F) and 100 MPa (15 ksi) for four hours. After depressurization of the vessel, the three cans were removed hot at 1070°C (1950°F) and air cooled.

The two additional cans representing IIb-11C were subjected to varying loading and pretreatment cycles to evaluate the effect of these variables on the same composition. As opposed to the initial IIb-11C can which was pretreated and hot loaded and unloaded, the second can was also pretreated at 980°C (1800°F) for two hours, but was cold unloaded (i.e., allowed to cool slowly in the autoclave). The third can was hot loaded and unloaded similar to the first, but was given no pretreatment. All five cans were pressed at the same temperature, pressure and time conditions. A listing of the consolidation handling variables is presented in Table 2, along with identity designations (C, C1, C2, D and E) for each of the five preforms.

b. Preliminary Rolling Studies

The five Federal-Mogul hot isostatically pressed preforms were machined for can removal to sizes of approximately 13 centimeters (5 in) in diameter and 13 centimeters (5 in) thick. One slice approximately 2 centimeters (0.75 in) thick was sectioned from each preform. The slices were further sectioned to yield four 2.5 centimeter (1 in) square pieces. These pieces were canned and variously cross rolled by four different procedures as follows:

- [1] Standard pass reductions from 1065°C (1950°F) with single passes between reheat.
- [2] 1245°C(2275°F)/2 hours/RAC + [1] above.
- [3] Standard pass reductions from 1065°C (1950°F) with double passes between reheat.
- [4] Standard pass reductions from 1120°C (2050°F) with single passes between reheat.

In each case the standard reduction sequences were five, five, seven, seven, nine, nine, nine, nine, ten and ten percent for a total of 55.7 percent.

The four rolled specimens from each of the five preforms were each solution treated at two temperatures: 1230°C (2250°F) and 1245°C (2275°F)/2 hours/RAC. A total of forty specimens were examined by optical microscopy to determine the effect of the rolling cycle variations on response to grain growth during heat treatment. The objective was to obtain grain sizes in the range of ASTM 4 to 5 after heat treatment of hot rolled material. Based on these evaluations, an optimum rolling sequence was determined for each of the five preforms.

c. Cross Rolling

One melt approximately 13 centimeters (5 in) in diameter by 5 centimeters (2 in) thick was sectioned from each of the five preforms and was canned as previously described in preparation for cross rolling. The canned preforms were hot rolled per selected procedures determined from the preliminary studies described above.

5. Heat Treatment Evaluation

a. Mechanical Property Survey

Eight heat treatment cycles were formulated for evaluation based on previous experience, and as mechanical property results were obtained. Mechanical test specimens and micro samples were sectioned from cross rolled disk material representing the five preforms. Material heat treated using the various cycles was tensile tested at 540°C (1000°F) and 760°C (1400°F), and stress rupture tested at 760°C/690 MPa (1400°F/100 ksi) and 815°C/485 MPa (1500°F/70 ksi). Approximately eighteen mechanical test specimens were evaluated at combinations of the above test conditions for each of the five preforms. Based on the mechanical test data, an optimum heat treatment cycle was selected for each of the five composition/consolidation combinations.

b. Structural Examinations

The best heat treatment selected for each of the preforms was further characterized by optical and electron microscopy and x-ray phase analyses. Procedures for these studies were detailed in a previous section of this report.

6. Mechanical Property Evaluation

Mechanical testing was conducted on each of the five composition/consolidation combinations after hot rolling to disks. Specimen blanks were sectioned from the cross rolled disks and heat treated by the best method determined from the heat treatment evaluation.

a. Tensile Tests

Duplicate tensile tests were conducted on as-heat treated material at room temperature, 540°C (1000°F), 650°C (1200°F), 760°C (1400°F) and 815°C (1500°F).

b. Stress Rupture Tests

Duplicate stress rupture tests were conducted on each as-heat treated disk at 650°C/1103 MPa (1200°F/160 ksi), 760°C/690 MPa (1400°F/100 ksi), 815°C/483 MPa (1500°F/70 ksi), and 870°C/345 MPa (1600°F/50 ksi).

7. Thermal Stability Evaluation

a. Thermal Cycle

Cross rolled disk product in the as-heat treated condition representing each of the five composition/consolidation combinations was subjected to a thermal exposure at 870°C (1600°F) for 1500 hours. Two tensile and two stress rupture blanks, in addition to material for structural examination, were exposed as indicated.

b. Mechanical Testing

Following the 1500 hour exposure at 870°C (1600°F), specimens were finish machined and duplicate tests were conducted in tension at 760°C (1400°F) and in stress rupture at 760°C/690 MPa (1400°F/100 ksi). Comparison of these data with corresponding as-heat treated property levels permitted determination of the direct effect of the exposure on 760°C (1400°F) properties.

c. Structural Examinations

Exposed material representing cross rolled product from each of the five composition/consolidation combinations was characterized by optical and electron microscopy and x-ray phase analysis. Procedures for this examination have been detailed previously.

8. Density Measurements

Density measurements were obtained on cross rolled product representing each of the composition/consolidation combinations. Measurements were taken using the water displacement method.

IV. RESULTS AND DISCUSSION

A. Task I - Evaluation of Alloys - Group I

1. Series I

a. Melting and Atomization

Melting and atomization of the four Task I - Series I compositions yielded approximately 40 kilograms (90 lbs.) of -60, +325 mesh powder from each heat after screening. A typical sieve analysis for these heats is listed in Table 3.

b. Chemical Analysis

Aim and actual chemical analyses for the four Task I - Series I heats are presented in Table 4. Actual analyses were within acceptable weight percent deviation ranges.

c. Processing

(1) First Trial

Canning, evacuation and hot isostatic pressing procedures were reported to proceed without difficulty by Battelle. The hot isostatic pressing temperatures and pressures are presented in Table 5 as a function of time. A total of approximately nine hours in the autoclave was required to accomplish the objective of a three hour cycle at 1150°C (2100°F) and 100 MPa (15 ksi). The appearance of the consolidated billets is illustrated in Figure 3.

After hot isostatic pressing, two preforms representing each composition were cross rolled a total of 56.7 percent using identical rolling temperatures and reductions for each preform. After decanning, it was observed that seven of the eight disks cracked catastrophically. Only one disk representing the IIb-IIb composition did not experience cracking. The two cross rolled IIb-IIb disks are shown in Figure 4. As cross rolling temperatures and reductions were identical for the two disks, cracking was believed to be related to inconsistencies in the original hot isostatically pressed preform.

Evaluations were conducted to establish the cause for the hot workability failures. Chemical analysis results are shown in Table 6 for several tramp elements and gas content. The four heats were all observed to contain acceptable levels of manganese, silicon, sulfur and phosphorus. No variations were observed which could be attributed to the workability failures. Analyses for argon, oxygen, hydrogen and nitrogen revealed gas contents slightly higher for the

IIb-11B disk which cracked, as compared to the disk which rolled well. However, the variations were slight and all levels were within generally acceptable limits. Detailed mass spectrographic analyses also failed to reveal trace element contamination which could be attributable to the failures.

Examination of fracture surfaces using scanning electron microscopy showed cracking associated with original powder particle boundaries, indicating inadequate compaction during the HIP cycle. This effect is illustrated in Figure 5. Information available at this time permitted no direct conclusion whether the inadequate compaction occurred as a result of consolidation temperature, improper degassing, or a combination of both.

(2) Second Trial

These trials were conducted using powder remaining from the original Task I - Series I heats. Hot isostatic pressing temperature was increased to 1200°C (2200°F) with pressure remaining the same at 100 MPa (15 ksi). The canning, degassing and pressing were conducted by Industrial Materials Technology (IMT) with no reported difficulty. A difference in pressing temperature monitoring procedure was noted between Battelle and IMT. The latter source shields and insulates thermocouples on a piece in the load, while the former does not. IMT reports that unshielded thermocouples indicate temperature as much as one to two hours sooner due to direct radiant exposure to the heating elements.

The preforms from the 1200°C (2200°F) pressing at IMT were canned and rolled with unsatisfactory results. Cracking occurred in all five disks, although the degree of cracking was substantially less than experienced in the first trial. Because of the workability improvement observed by increasing the hot isostatic pressing temperature from 1150°C (2100°F) to 1200°C (2200°F), it was concluded the poor workability experienced in the Task I - Series I trials was due primarily to inadequate pressing temperature. A decision was made to remelt the Task I heats and reevaluate utilizing an increased compaction temperature during the consolidation cycle.

2. Series II

a. Melting and Atomization

Remelting of the four Task I compositions produced 32 kilograms (70 lbs) of -60, +325 mesh powder from each heat. A sieve analysis similar to that listed in Table 1 was obtained.

b. Chemical Analysis

Table 1 lists the target and actual chemical analyses for the four Task I -

Series II heats are presented in Table 7. All values were within acceptable limits, although the hafnium in IIb-11A at 1.65 percent was lower than the desired 2.0 percent.

c. Processing

(1) Hot Isostatic Pressing

Canning, evacuation, and hot isostatic pressing was conducted by IMT with no report of difficulty. Parameters of 1230°C (2250°F) and 100 MPa (15 ksi) for six hours were achieved as requested. This represented an increase in temperature and time from the previous trial parameters of 1200°C (2200°F) for two hours in an effort to effect better bonding of the powder particles.

(2) Cross Rolling

Two pieces from each of the four preforms were rolled using Task I - Series I temperatures and reductions. The workability of all eight disks was excellent as illustrated in Figure 6.

(3) Structural Examinations

Examination of optical micrographs representing the edge, mid-radius and center locations of an as-rolled disk from each composition revealed good microstructural uniformity. No variations in carbide or gamma prime distribution were observed in any of the disks as a function of location.

d. Heat Treatment Evaluations

(1) Selection of Optimum Treatment

The effect of full solution treatments varying temperature and time on the ASTM grain size of material from each composition is illustrated in Table 8. Regardless of temperature or time, all grain size values were finer than ASTM 5. These results are significantly different from those observed on conventionally produced wrought material where a grain size of ASTM 4.5 was attainable by solution treatment at 1230°C (2250°F)/4 hours/RAC. The difference is attributed to the uniform fine dispersion of carbides in all four powder alloys, which served to inhibit grain boundary migration and growth. This is contrasted to random larger carbide particles in wrought product, which do not approach the number of particles per unit area in powder product. Based on the heat treat survey, full solution treatments chosen for each alloy were as follows: 1230°C (2250°F)/4 hours/RAC for alloys IIb-11 and IIb-11S, 1220°C (2225°F)/60 hours/RAC for IIb-11A, and 1245°C (2275°F)/2 hours/RAC for

IIb-11B. These treatments were selected to yield the maximum grain sizes attainable for each alloy with no evidence of incipient melting. It should be noted that 1260°C (2300°F) solution treatments resulted in some evidence of melting for all alloys but ASTM grain sizes were not measurably coarsened.

The intermediate aging treatment selected for all four alloys was 1040°C (1900°F)/2 hours/RAC. The 870° and 900°C (1600° and 1650°F) intermediate treatments resulted in excessive grain boundary carbide precipitation for all four compositions. The 1040° and 1065°C (1900° and 1950°F) treatments were observed to yield slightly coarser gamma prime particle distributions in each of the alloys. The degree of coarsening, however, was less significant at 1040°C (1900°F). The selected treatment varied considerably from the 870°C (1600°F)/16 hour/RAC treatment designed for wrought product. As was the case for the full solution treatment, significant structural variations were observed between powder and wrought material.

As previously noted, a final aging treatment of 760°C (1400°F)/16 hours/AC was chosen for each composition based on previous studies.

(2) Structural Examinations

Optical micrographs illustrating each alloy heat treated by the selected method are shown in Figure 7. Corresponding electron micrographs are illustrated in Figures 8, 9, 10, and 11 for alloys IIb-11, IIb-11S, IIb-11A and IIb-11B, respectively. Structures for IIb-11 and IIb-11S were very similar with duplex grain sizes in the ASTM 5 to 7 size range. Grain sizes for both IIb-11A and IIb-11B were finer in the ASTM 6 to 7 range, with grain growth inhibited in IIb-11A by random primary gamma prime pools and in IIb-11B by a heavy distribution of fine carbides. All compositions displayed both first and second generation gamma prime. As noted previously, the low carbon - high hafnium IIb-11A displayed a distribution of primary gamma prime pools at grain boundary triple points. Gamma prime size was generally finer for IIb-11 and IIb-11S as compared with coarser distributions in the other two alloys. Additionally, some evidence of thermally induced porosity (TIP) was observed in all the alloys, but was most prevalent in IIb-11A (see Figure 7). TIP is usually attributed to either excessive argon entrapment in coarse, hollow powder particles or to inadequate hot evacuation prior to consolidation. However, in these instances, the TIP is almost entirely concentrated in grain boundary areas as opposed to within grains; and, therefore, appears to have resulted from inadequate evacuation.

The results of extraction and X-ray phase analysis are listed in Table 9 for as-heat treated material representing each composition. All four compositions contained MC-type carbides, with the largest concentration predictably in the high carbon IIb-11B composition. The only as-heat treated alloy containing another minor constituent was IIb-11S, which contained a small concentration of M₆C-type carbides. The gamma prime constituent is present in all compositions, but is not listed in Table 9 because the 10 percent hydrochloric acid in methanol solution used in the extraction dissolves this intermetallic compound.

e. Mechanical Testing

(1) Tensile Tests

Tensile properties for the four compositions in the as-heat treated condition are summarized in Tables 10, 11, 12 and 13 and are illustrated in Figure 12. Powder metallurgy NASA IIb-11 and IIb-11B display similar tensile strength and ductility with NASA IIb-11S slightly lower in both strength and ductility. NASA IIb-11A is the weakest of the four compositions and shows significant decreases in both strength and ductility at elevated temperatures.

Also illustrated in Figure 12 are comparison points for conventionally produced wrought NASA IIb-11. While ultimate tensile strength values for the powder alloys IIb-11, IIb-11S and IIb-11B are higher than the wrought material at room temperature, the powder alloys were all weaker than wrought NASA IIb-11 at 760°C (1400°F). The powder alloys also showed less than half the tensile ductility of the wrought material at that same temperature.

(2) Stress and Creep Rupture Tests

Stress and creep rupture data for the four powder compositions are summarized in Tables 14, 15, 16 and 17. The NASA IIb-11 properties were the best of the four powder alloys evaluated. However, the 760°C/620 MPa (1400°F/90 ksi) rupture life of the best powder alloy was approximately one-fifth the 500 hour life displayed by wrought material of the same composition.

f. Thermal Stability Evaluations

(1) Mechanical Testing

Tensile and stress rupture data at 760°C (1400°F) for the Task I - Series II compositions in the heat treated and heat treated plus exposed conditions are summarized in Tables 18 and 19, respectively. Tensile and yield strength values decreased as a result of the exposure by approximately 10 to 15 percent for compositions IIb-11, IIb-11S and IIb-11B; tensile ductility values also decreased for these compositions. Strength and ductility values

for IIb-11A were increased after the exposure; however, values in the heat treated condition were substantially lower than the other three alloys. This behavior was apparently due to the extremely brittle characteristics of this composition, which prevented the inherent strength from being measured.

Stress rupture life values decreased after exposure to approximately 60, 25 and 60 percent of the as-heat treated values for IIb-11, IIb-11S and IIb-11B, respectively. IIb-11A life increased slightly as a result of the exposure. The values, however, were significantly lower than those displayed for the other three compositions again probably for the same reason as noted above. Rupture ductilities were not appreciably affected as a result of the exposure for IIb-11, IIb-11S or IIb-11A; however, values for IIb-11B were decreased.

(2) Structural Examinations

Optical micrographs illustrating the appearance of the four compositions after exposure are presented in Figure 13. Electron micrographs are shown in Figures 14, 15, 16 and 17. All the compositions were observed to display gamma prime coarsening with some evidence of agglomeration. Coarsening was more significant for alloys IIb-11A and IIb-11B. Also, the exposure resulted in increased degrees of grain boundary carbide precipitation in three of the alloys. Only IIb-11A did not experience grain boundary precipitation; the primary gamma prime pools observed in the as-heat treated microstructure of this alloy remained after exposure. A needle-like phase was observed in the IIb-11 microstructure.

Results of X-ray phase analyses after exposure are presented in Table 9 with results for as-heat treated material. These findings were in agreement with trends observed in the microstructure and discussed above. Increased amounts of M_6C grain boundary carbides were identified in all of the alloys as a result of the exposure. This was generally accomplished by the decomposition of MC carbides. The needle-like phase observed in the IIb-11 microstructure was found to be a tungsten-rich mu phase (M_7M_6 -type). Several unidentified lines may indicate the presence of mu phase in IIb-11B, although the low intensity of the lines did not permit positive identification.

g. Density Measurements

Density measurements for the four Task I - Series II alloys are listed in Table 20. Values were essentially the same at 8.71 g/cm^3 (0.314 lbs/in^3) for IIb-11 and IIb-11S, while the increased hafnium in IIb-11A and IIb-11B resulted in density increases to 8.74 and 8.76 g/cm^3 (0.315 and 0.316 lbs/in^3), respectively.

h. Data Analysis

A review of the data generated in Task I indicated that none of the four compositions displayed properties which justified scale-up and detailed study in Task II. Both tensile and stress rupture properties were substantially lower than those characteristic of wrought material in the previous study. As a result, a decision was made to modify the original plan and evaluate additional compositional changes in Task II alloys. Since fine grain size was a primary reason for the failure to achieve desired properties, processing variables were incorporated in an effort to attain coarser grain sizes in Task II alloys.

B. Task II - Evaluation of Alloys - Group II

1. Melting and Atomization

Melting and atomization of the three Task II compositions yielded approximately 60 kilograms (130 lbs) of useable powder for IIb-11C and 25 kilograms (55 lbs) each for IIb-11D and IIb-11E. Sieve analyses for the three heats screened to -60, +325 mesh were similar to the analysis presented in Table 3.

2. Chemical Analysis

Aim and actual chemical analyses for the three Task II heats are illustrated in Table 21. Results for all heats were well within desired ranges, especially for the variable elements carbon and hafnium.

3. Processing

a. Hot Isostatic Pressing

Five preforms including three of the IIb-11C composition and one each representing IIb-11D and IIb-11E were obtained after canning, hot evacuation and hot isostatic pressing by Federal-Mogul. Variations which included hot and cold unloading as well as a high temperature HIP pretreatment as outlined in Table 2 were accomplished as requested. The appearance of the as-pressed preforms is illustrated in Figure 18.

b. Preliminary Rolling Studies

Four practices were formulated with the objective of improving the response of the materials to grain coarsening during subsequent solution treatments. Practice [1] represented the standard ten single pass sequence from a 1065°C (1950°F) rolling temperature. Practice [2] employed a 1245°C (2275°F) pretreatment prior to rolling as in [1] in an effort to coarsen grain size prior to rolling. Practice [3] was formulated as a slight variation from [1] with double passes per reheat in an attempt to generate more strain in the cross rolled material. It was theorized that this strain might accentuate the reactions during

subsequent solution treatment and effect increased grain growth. Practice [4] was also similar to [1], although rolling was conducted from 1120°C (2050°F) to effect more solutioning and less grain refinement during rolling.

The effect of the four preliminary rolling practices on hot workability is illustrated in Figure 19 for each of the samples rolled from the five preforms. Practices [1], [3], and [4] all displayed satisfactory workability. Some edge cracking appeared on random pieces, but this condition was attributed to premature deterioration of the protective can. Practice [2] resulted in very poor hot workability for all five preforms. This was due to the effect of the high degree of solutioning at 1245°C (2275°F) followed by rapid cooling. This practice permitted large amounts of gamma prime to be solutioned and held in solution by rapid cooling. The amount of gamma prime remaining in solution was excessive for these highly-alloyed compositions. No definite trends were derived regarding comparison workability of the five preforms using a given practice.

The effect of solutioning treatments on ASTM grain size for preforms cross rolled using the four preliminary practices is illustrated in Table 22. These results indicate practice [4] with a 1245°C (2275°F) solution treatment yielded the largest grain sizes. While the effect was only slight for composition IIb-11C preforms (C, C1 and C2), compositions IIb-11D and IIb-11E attained target grain sizes in the ASTM 4 to 5 range. The grain coarsening tendencies for the latter two compositions is probably due to their lower carbon contents at 0.055 percent compared with 0.095 percent for IIb-11C. No significant effects on grain sizes were apparent regarding single versus double passes per reheat from 1065°C (1950°F), and no effects were observable among the three IIb-11C preform variations. The 1245°C (2275°F) solutioning treatment generally resulted in more appreciable grain growth than the 1230°C (2250°F) treatment, although the effects were most significant for the low carbon compositions.

Based on a combination of workability and response to solution treatment, practice [4] involving rolling from 1120°C (2050°F) was chosen as the optimum cross rolling practice for each preform variation.

c. Cross Rolling

The appearance of disks representing each of the five preform variations after cross rolling and decanning is illustrated in Figure 20. The workability of all disks was rated excellent; no cracking was observed on any of the disks.

4. Heat Treatment Evaluation

a. Mechanical Property Survey

The eight heat treatment cycles evaluated for each disk are listed in Table 23. Mechanical property data obtained on each of the five cross rolled disks heat treated by these various cycles are summarized in Tables 24 through 28. Initial trials for treatments [A] and [B] versus [C] and [D] showed the 870°C (1600°F) intermediate aging treatment to be superior to the 1040°C (1900°F) age for 760°C (1400°F) stress rupture properties. More detailed evaluation of the 870°C (1600°F) aging with 1230°C (2250°F) and 1245°C (2275°F) solution treatments ([A] versus [B]) indicated that 760°C (1400°F) stress rupture life values were substantially lower than desired, regardless of solution treatment temperature. Values were in the 25 hour range for the high carbon preforms (C, C1 and C2), while the lower carbon preforms (D and E) displayed higher life values, but only in the 70 hour range. Based on optical microscopy examination, it was determined that excessive grain boundary carbide precipitation was occurring during the 870°C (1600°F) age. Therefore, four additional cycles were formulated in an effort to minimize this condition by elimination [E], modification to a 955°C (1750°F) age [F], or varying cooling rates from the solution temperature prior to the 870°C (1600°F) age [G and H]. The latter two cycles were formulated to effect more stable MC carbide precipitation at higher temperatures during the slower furnace cools, thus leaving less carbon in solution and available for precipitation during aging.

Results for cycles [E] and [F] were again less than desired; however cycles [G] and [H] resulted in substantial 815°C (1500°F) rupture life increases for all five preforms. Tensile strength values at 540°C (1000°F) were approximately 5 percent lower than values achieved with direct rapid air cooling from solution treatment temperatures; however, tensile and stress rupture ductility values were increased, especially for preforms D and E. Based on significantly higher rupture life and ductility in spite of slightly lower yield strength, cycle [G] was chosen as the optimum treatment for all five preforms.

b. Structural Examinations

The microstructures of the three preforms prepared from IIB-11C (C, C1 and C2) were essentially the same after heat treatment. Optical micrographs representing preforms of each composition are illustrated in Figure 21. Electron micrographs for corresponding as-heat treated compositions are shown in Figure 22. After treatment [G], the microstructures displayed unique coarse gamma prime distributed within grains, and also oriented as discrete precipitates along grain boundaries. Carbide distribution appeared to be primarily a random dispersion of fine particles, with no evidence of significant grain boundary precipitation in any of the preforms. Grain size measurements corresponded reasonably well with preliminary rolling study results with high carbon preforms C, C1 and C2 measuring in the ASTM 6 range and low carbon preforms D and E in the ASTM 4 to 5 range. Some degree of TIP was detected in all preforms after heat treatment, but was most severe in preform D.

X-Ray phase analysis results for as-heat treated Task II disks are summarized in Table 29. Again, results for all three IIb-11C preforms (C, C1 and C2) were similar. In fact, the phases present after cycle [G] heat treatment were basically the same and in the same quantities for all five preforms. In all cases, the primary constituent was MC carbide; much lesser quantities of M₆C and M₂₃C₆ carbides were also present for each preform. These results indicate the objective of heat treatment cycle [G] to permit precipitation of more stable MC carbides during slow cooling was achieved. For each preform, the lesser amounts of carbon available in solution after slow cooling resulted in only minor quantities of the grain boundary carbides precipitating during aging.

5. Mechanical Property Evaluation

a. Tensile Tests

Tensile test results for the five Task II cross rolled disks are presented in Tables 30 through 34. As results for the three IIb-11C disks were similar, data for disks from preforms C, D and E representing each of the three compositions are illustrated graphically in Figure 23. These data show that alloy IIb-11C displays slightly higher ultimate and yield strength values than IIb-11D and IIb-11E, although the variations appear to be of little significance. In respect to tensile ductility, IIb-11E values were the highest of the three compositions, especially in the 760° to 815°C (1400° to 1500°F) range.

Comparison points for the wrought IIb-11 composition at room temperature and 760°C (1400°F) are also shown on Figure 23. These points indicate similar strength when comparing wrought material with the powder alloys. However, the yield strength of the wrought material was higher than the powder alloys at both room temperature and at 760°C (1400°F). The IIb-11E composition displayed significantly higher elongation values than the wrought material at room temperature and 760°C (1400°F).

b. Stress Rupture

Stress rupture data for the five Task II cross rolled disks are summarized in Tables 35 through 39 and are illustrated in Figure 24. Results for the three IIb-11C preforms were similar, and only the disk from preform C was included for comparison with disks from preforms D and E in Figure 24. These data show IIb-11E displaying the best rupture strength of the three Task II alloys. Differences among the alloys were less significant at low temperature/high stress parameters, but became more substantial at high temperature/low stress parameters. For example, average 870°C/345 MPa (1600°F/50 ksi) rupture life values for IIb-11C, IIb-11D and IIb-11E were 6, 26 and 67 hours, respectively. Rupture ductility values for compositions IIb-11D and IIb-11E were similar, and were higher than those displayed by IIb-11C.

Comparison of rupture strength between the best of the powder alloys, IIb-11E, and wrought IIb-11 indicated the wrought material was slightly stronger than the IIb-11E. Based on estimates from the parameter curves, this difference would be 170 versus 140 hours for wrought IIb-11 and IIb-11E, respectively, at 760°C/690 MPa (1400°F/100 ksi). At conditions of 760°C/620 MPa (1400°F/90 ksi), rupture life values would be approximately 500 and 425 hours for wrought IIb-11 and IIb-11E, respectively. Rupture ductility for the powder IIb-11E was better than wrought IIb-11 at 760°C (1400°F).

6. Thermal Stability Evaluation

a. Mechanical Testing

Results of 760°C (1400°F) tensile tests before and after exposure at 870°C (1600°F)/1500 hours are summarized in Table 40 for the Task II compositions. Material from the three IIb-11C disks and composition IIb-11D experienced ultimate tensile and yield strength losses of about 25 percent, while strength losses for IIb-11E were less severe in the 15 percent range. Ductilities for all compositions decreased by at least 50 percent.

Stress rupture results before and after exposure are presented in Table 41. These data show rupture life values decreasing approximately 90 percent after exposure for all three compositions. Rupture ductility values for the three IIb-11C cross rolled disks were not substantially affected, while values for IIb-11D were decreased and IIb-11E increased somewhat as a result of the exposure.

b. Structural Examinations

As was the case prior to exposure, optical and electron micrographs for the three IIb-11C cross rolled disks displayed similar structures. Optical micrographs are presented in Figure 25 and electron micrographs in Figure 26 for material obtained from preforms C, D and E representing the three Task II compositions after exposure. The most apparent changes, compared with as-heat treated structures (see Figures 21 and 22), include the presence of nearly continuous grain boundary carbides in addition to coarsening and agglomeration of gamma prime in all three compositions. Gamma prime particles have become more rounded as opposed to the angular precipitates in as-heat treated materials; and the fine, second generation gamma prime precipitates have agglomerated and are no longer visible after exposure.

The results of x-ray phase analyses for the five cross rolled disks before and after exposure are presented in Table 29. Each of the disks experienced decomposition of their primary constituent, MC, in all cases resulting in the formation of significant amounts of M₆C and lesser amounts of M₂₃C₆ in the grain boundaries. The three IIb-11C preforms and IIb-11D also formed minor amounts of M₇M₆-type mu phase. No mu phase was detected in IIb-11E.

These results, in combination with mechanical testing results for exposed materials, pose a question regarding the validity of the "accelerated" 870°C (1600°F) thermal exposure. This treatment was formulated in the past for wrought materials to obtain some measure of the materials' stability after long-time service. While the materials will be in service in the 760°C (1400°F) range, 870°C (1600°F) was used to "accelerate" the exposure so a measure could be obtained after 1500 hours. This procedure was acceptable for wrought materials where carbide morphology was substantially different than for powder materials. Wrought techniques resulted in random, large carbide particles distributed throughout the matrix of the alloys. The number of carbides per unit area was significantly less than for powder alloys, which display a uniform, dense dispersion of extremely fine carbides, with a much higher number of carbides per unit area. It is well recognized that the decomposition of MC carbides into less stable grain boundary M_6C and $M_{23}C_6$ carbides will occur to a much greater degree at 870°C (1600°F) than 760°C (1400°F). While the accelerated treatment in wrought alloys resulted in MC decomposition, formation of the less stable carbides was primarily localized near random, large MC particles which were decomposing. In the case of powder alloys, decomposition of the fine dispersion of MC carbides results in the formation of grain boundary carbides uniformly throughout the microstructures. As a result, exposure at 760°C (1400°F) for 10,000 hours might be far less damaging than exposure at 870°C (1600°F) for 1500 hours, due to the increased stability of the MC carbides at the lower temperature.

7. Density Measurements

The results of density measurements on disks representing the five Task II preforms are listed in Table 42. Values for the three IIb-11C compositions and IIb-11E were 8.75 g/cm^3 (0.316 lbs/in^3), while IIb-11D density was slightly higher at 8.79 g/cm^3 (0.317 lbs/in^3).

V. SUMMARY OF RESULTS

The objective of this program was to optimize the NASA IIb-11 composition, an alloy originally developed as a conventional cast and wrought material, for thermal stability and to determine the feasibility for producing the alloy using powder metallurgical techniques. The results of the program are presented below:

1. The best composition developed was low carbon-low hafnium IIb-11E. The alloy composition includes 0.06 C, 8.5 Cr, 9.0 Co, 2.0 Mo, 7.1 W, 6.6 Ta, 4.5 Al, 0.75 Ti, 0.5 V, 0.7 Hf, 0.01 B, 0.05 Zr and balance Ni. The alloy attained 760°C (1400°F) mechanical property levels comparable with conventional cast and wrought IIb-11, although properties were reduced after a 870°C (1600°F) exposure for 1500 hours.
2. HIP loading/unloading variables including hot and cold transfer had no significant effects on the mechanical properties or microstructure.
3. Cross rolling from 1120°C (2050°F) rather than 1065°C (1950°F) resulted in improved response to grain growth during the solution heat treatment. A lower rolling temperature of 1065°C (1950°F) is used for the wrought version of these alloys.
4. The best heat treatment for wrought material was undesirable for powder material. This treatment employed a rapid air cool after the solution treatment which held carbon in solution and effected excessive grain boundary carbide precipitation during aging treatments.
5. Slow cooling from solution treatments resulted in substantial improvements in rupture strength and tensile and rupture ductility for the powder alloys; yield strength decreased slightly. The delayed cooling may have promoted precipitation of stable MC carbides at higher temperatures; consequently, less carbon was available in solution for continuous precipitation in grain boundaries during aging.
6. The low carbon (0.055 percent) alloys IIb-11D and IIb-11E exhibited better grain coarsening response during solution treatment than the high carbon (0.095 percent) IIb-11C.

VI. CONCLUDING REMARKS

The combination of tensile and stress rupture strength and ductility of NASA IIb-1E suggests potential for advanced powder metallurgy disks operating in the 760°C (1400°F) range. Although the present study explored only a few combinations of cross rolling parameters and heat treatment cycles, the 760°C (1400°F) rupture strength of NASA IIb-1E is higher than any commercial or experimental powder metallurgy alloy reported in the literature. The alloy is not susceptible to TCP (topologically close-packed) phase formation after thermal exposure at 870°C (1600°F) for 1500 hours. However, mechanical properties are lowered due to an excessive formation of grain boundary carbides. Further modifications to the heat treatment may permit increased strength, particularly yield strength, without adversely affecting rupture characteristics. Studies are also recommended to determine the validity of the "accelerated" 870°C (1600°F) treatment for alloys of this type designed for service at 760°C (1400°F).

The results of this program demonstrate the importance of determining optimum parameters for the hot isostatic pressing (HIP) temperature and hot evacuation procedures prior to HIP. It was experienced that both poor hot workability and adverse structural effects can result in alloys of this type if minimum HIP temperatures and holding times are not attained.

REFERENCES

1. Kent, W. B., "Wrought Nickel-Base Superalloys", NASA CR-72687, Universal-Cyclops Specialty Steel Division, Cyclops Corporation, March, 1970.
2. Kent, W. B., "Development Study of Compositions for Advanced Wrought Nickel-Base Alloys", NASA CR-120934, Universal-Cyclops Specialty Steel Division, Cyclops Corporation, January 1972.
3. Woodyatt, L. R., C. T. Sims and H. J. Beattie, Jr., "Prediction of Sigma-Type Phase Occurrence From Compositions in Austenitic Superalloys", Transactions AIME, 236 (April, 1966), 519-527.
4. Miner, R. V., "Effects of Carbon and Hafnium Concentrations in Wrought Powder-Metallurgy Superalloys Based on NASA IIb-11 Alloy", NASA TND-8113, January, 1976.

TABLE 1

Summary of Selected Compositions for Task I and Task II Evaluations

<u>Alloy Identification</u>	Chemical Composition (Weight Percent) For:													
	<u>C</u>	<u>Cr</u>	<u>Co</u>	<u>Mo</u>	<u>W</u>	<u>Ta</u>	<u>Al</u>	<u>Ti</u>	<u>V</u>	<u>Hf</u>	<u>B</u>	<u>Zr</u>	<u>Ni</u>	<u>Nv</u>
<u>Task I Compositions:</u>														
NASA IIb-11	0.130	9.0	9.0	2.0	7.5	7.0	4.5	0.75	0.5	1.0	0.02	0.10	Balance	2.22
NASA IIb-11S	0.130	9.0	9.0	2.0	7.0	7.0	4.3	0.75	0.4	1.0	0.02	0.10	Balance	2.12
NASA IIb-11A	0.080	9.0	9.0	2.0	6.0	7.0	4.3	0.75	0.4	2.0	0.02	0.10	Balance	2.14
NASA IIb-11B	0.200	9.0	9.0	2.0	7.0	7.0	4.3	0.75	0.4	2.0	0.02	0.10	Balance	2.14
<u>Task II Compositions:</u>														
NASA IIb-11C	0.095	8.5	9.0	2.0	7.1	6.6	4.5	0.75	0.5	1.3	0.01	0.05	Balance	2.15
NASA IIb-11D	0.055	8.5	9.0	2.0	7.1	6.6	4.5	0.75	0.5	1.3	0.01	0.05	Balance	2.17
NASA IIb-11E	0.055	8.5	9.0	2.0	7.1	6.6	4.5	0.75	0.5	0.7	0.01	0.05	Balance	2.13

34

TABLE 2

Task II HIP Handling Variables

<u>Preform Code</u>	<u>Alloy Designation</u>	<u>VARIABLES</u>	
		<u>HIP Pretreatment</u>	<u>HIP Loading/Unloading</u>
C	<i>IIb-11C</i>	<i>980°C (1800°F)/2 hours</i>	<i>HOT</i>
C1	<i>IIb-11C</i>	<i>980°C (1800°F)/2 hours</i>	<i>COLD</i>
C2	<i>IIb-11C</i>	<i>NONE</i>	<i>HOT</i>
D	<i>IIb-11D</i>	<i>980°C (1800°F)/2 hours</i>	<i>HOT</i>
E	<i>IIb-11E</i>	<i>980°C (1800°F)/2 hours</i>	<i>HOT</i>

*HIP Cycle for all preforms: 1245°C (2275°F) and 100 MPa (15 ksi) for four hours.

65

TABLE 3

Typical Sieve Analysis For Argon Atomized Powder Heats

<u>SIEVE SIZE</u>		<u>% OF TOTAL BLEND</u>
	+ 80	13
- 80	+100	14
-100	+140	21
-140	+200	24
-200	+325	27

hg

TABLE 4

Aim and Actual Chemical Analyses For Task I-Series I Powder Heats

Heat Identification	Chemical Composition (Weight Percent) For:													
	C	Cr	Co	Mo	W	Ta	Al	Ti	V	Hf	B	Zr	Ni	O ₂
NASA IIb-11 (Aim)	0.13	9.00	9.00	2.00	7.50	7.00	4.50	0.75	0.50	1.00	0.02	0.10	Balance	
KR 234	0.13	9.00	9.00	1.91	7.64	7.01	4.58	0.70	0.47	0.97	0.02	0.10	Balance	38 ppm
NASA IIb-11S (Aim)	0.13	9.00	9.00	2.00	7.00	7.00	4.30	0.75	0.40	1.00	0.02	0.10	Balance	
KR 235	0.12	9.03	9.07	1.92	7.12	6.98	4.27	0.70	0.39	0.97	0.02	0.11	Balance	38 ppm
NASA IIb-11A (Aim)	0.08	9.00	9.00	2.00	6.00	7.00	4.30	0.75	0.40	2.00	0.02	0.10	Balance	
KR 236	0.08	9.09	9.18	1.96	6.30	7.18	4.25	0.74	0.40	1.95	0.02	0.11	Balance	59 ppm
NASA IIb-11B (Aim)	0.20	9.00	9.00	2.00	7.00	7.00	4.30	0.75	0.40	2.00	0.02	0.10	Balance	
KR 237	0.19	9.00	9.06	2.03	6.98	7.20	4.40	0.70	0.39	1.96	0.02	0.11	Balance	71 ppm

35

TABLE 5

Task I - Series I Hot Isostatic Pressing Cycle

TIME (hours)	Temperature (°C) at Location:				
	T/C-1	T/C-2	T/C-5	T/C-6	Pressure (MPa)
START	--	~23	--	--	2
1	--	~200	--	--	2
3	600	596	597	638	2
4	800	805	810	810	12 (a)
5	910	890	926	921	46
6	1152	1152	1056	1052	101 (b)
6.15	1153	1150	1154	1150	103 (c)
7.15	1150	1149	1150	1150	103
8.15	1149	1148	1147	1147	103
9.15	1145	1149	1144	1150	103 (d)

- (a) Started pressure with compressors.
- (b) Compressors turned off.
- (c) Initiation of three hour cycle.
- (d) Heat turned off and gas slowly reclaimed overnight.

*Thermocouple location key:

T/C-1, top of load
 T/C-2, bottom of load
 T/C-5, middle of load
 T/C-6, 15 cm below load

TABLE 6

Tramp Element and Gas Contents For Various Cross Rolled Disks

<u>Alloy Designation</u>	<u>Heat Number</u>	<u>Disk Condition</u>	<u>Composition (wt.%) for:</u>				<u>Gas Content (ppm)</u>			
			<u>Mn</u>	<u>Si</u>	<u>S</u>	<u>P</u>	<u>Ar</u>	<u>O</u>	<u>H</u>	<u>N</u>
<i>IIb-11</i>	KR234	<i>Cracked</i>	<0.01	0.14	0.002	<0.002				
<i>IIb-11S</i>	KR235	<i>Cracked</i>	<0.01	0.14	0.002	<0.002				
<i>IIb-11A</i>	KR236	<i>Cracked</i>	<0.01	0.14	0.003	<0.002				
<i>IIb-11B</i>	KR237	<i>Cracked</i>	<0.01	0.14	0.003	<0.002				
<i>IIb-11B</i>	KR237	<i>OK</i>					0.64	44	1.5	24
<i>IIb-11B</i>	KR237	<i>Cracked</i>					0.75	56	1.9	47

15

TABLE 7

Aim and Actual Chemical Analyses For Task I - Series II Powder Heats

Heat Identification	Chemical Composition (Weight Percent) For:													
	C	Cr	Co	Mo	W	Ta	Al	Ti	V	Hf	B	Zr	O ₂	Ni
NASA IIb-11 (Aim)	0.13	9.00	9.00	2.00	7.50	7.00	4.50	0.75	0.50	1.00	0.02	0.100		Balance
KR 264	0.13	9.04	9.20	1.94	7.52	7.05	4.54	0.73	0.47	1.03	0.02	0.091	43 ppm	Balance
NASA IIb-11S (Aim)	0.13	9.00	9.00	2.00	7.00	7.00	4.30	0.75	0.40	1.00	0.02	0.100		Balance
KR 290	0.12	9.00	9.05	1.95	7.02	7.04	4.28	0.68	0.39	0.98	0.02	0.100	59 ppm	Balance
NASA IIb-11A (Aim)	0.08	9.00	9.00	2.00	6.00	7.00	4.30	0.75	0.40	2.00	0.02	0.100		Balance
KR 266	0.09	8.99	9.20	1.92	5.95	6.95	4.30	0.72	0.39	1.65	0.02	0.082	52 ppm	Balance
NASA IIb-11B (Aim)	0.20	9.00	9.00	2.00	7.00	7.00	4.30	0.75	0.40	2.00	0.02	0.100		Balance
KR 267	0.20	9.04	9.20	1.93	7.01	7.10	4.46	0.72	0.37	1.97	0.02	0.100	48 ppm	Balance

26

TABLE 8

Effect of Full Solution Heat Treatment on Grain Size of Task I - Series II Alloys

Treatment	ASTM Grain Size for Composition:			
	IIB-11	IIB-11S	IIB-11A	IIB-11B
1220°C (2225°F)/2 hours/RAC	7	7	7	7
1220°C (2225°F)/60 hours/RAC	6.5	6.5	6.5	7
1230°C (2250°F)/2 hours/RAC	50%5,50%7	50%5,50%7	6.5	7
1230°C (2250°F)/4 hours/RAC	80%5,20%7	70%5,30%7	6	7
1230°C (2250°F)/24 hours/RAC	6	6	6	7
1245°C (2275°F)/2 hours/RAC	50%5,50%7	6	6	7
1260°C (2300°F)/2 hours/RAC	50%5,50%7	70%5,30%7	6	7.5
1260°C (2300°F)/6 hours/RAC	50%5,50%7	70%5,30%6	70%5.5,30%7	7

39

TABLE 9

Results of X-Ray Phase Analyses For Task I - Series II Alloys
in the Heat Treated and Heat Treated Plus Exposed Condition

<u>Alloy Designation</u>	<u>Material Condition*</u>	<u>Relative Concentration** of Phases Present:</u>		
		<u>MC</u>	<u>M₆C</u>	<u>Mu</u>
<i>IIb-11</i>	H/T	<i>M</i>		
<i>IIb-11</i>	H/T + Exposed	<i>W</i>	<i>W</i>	<i>W</i>
<i>IIb-11S</i>	H/T	<i>M</i>	<i>W</i>	
<i>IIb-11S</i>	H/T + Exposed	<i>W</i>	<i>M</i>	
<i>IIb-11A</i>	H/T	<i>M</i>		
<i>IIb-11A</i>	H/T + Exposed	<i>W</i>	<i>W</i>	
<i>IIb-11B</i>	H/T	<i>S</i>		
<i>IIb-11B</i>	H/T + Exposed	<i>S</i>	<i>W</i>	<i>VW?</i>

* *S* represents Strong; *M*, Moderate; *W*, Weak; and *V*, Very.

** H/T indicates Heat Treated (detail below); Exposed indicates 870°C (1600°F)/1500 hours.

IIb-11, 1230°C (2250°F)/4 hours/RAC + 1040°C (1900°F)/2 hours/RAC + 760°C (1400°F)/16 hours/AC.
IIb-11S, 1230°C (2250°F)/4 hours/RAC + 1040°C (1900°F)/2 hours/RAC + 760°C (1400°F)/16 hours/AC.
IIb-11A, 1220°C (2225°F)/60 hours/RAC + 1040°C (1900°F)/2 hours/RAC + 760°C (1400°F)/16 hours/AC.
IIb-11B, 1245°C (2275°F)/2 hours/RAC + 1040°C (1900°F)/2 hours/RAC + 760°C (1400°F)/16 hours/AC.

TABLE 10

Tensile Properties For As-Heat Treated NASA IIb-11

Test Temperature °C	°F	Ultimate Tensile Strength		0.2% Yield Strength		Elongation (%)	Reduction of Area (%)
		MPa	ksi	MPa	ksi		
21	70	1585	229.8	1234	179.2	11.2	13.1
21	70	1516	219.9	1193	172.9	10.2	13.4
650	1200	1467	212.7	1124	163.2	5.7	13.6
650	1200	1446	209.7	1117	161.7	7.3	12.7
760	1400	1255	181.9	1083	157.1	5.0	10.7
760	1400	1276	184.7	1096	159.3	5.2	10.2
870	1600	710	102.7	696	100.8	--*	--*
870	1600	876	126.8	710	102.9	--*	--*

H
*Broke in shoulder.

TABLE 11

Tensile Properties For As-Heat Treated NASA IIB-11S

Test Temperature		Ultimate Tensile Strength		0.2% Yield Strength		Elongation (%)	Reduction of Area (%)
°C	°F	MPa	ksi	MPa	ksi		
21	70	1517	219.9	1155	167.5	11.4	17.2
21	70	1441	208.8	1117	162.6	9.5	9.6
650	1200	1338	194.2	1096	159.2	5.4	11.5
650	1200	1379	199.9	1076	155.6	6.9	11.2
760	1400	1338	164.6	1083	157.0	2.0	2.5
760	1400	1055	152.9	1014	146.7	1.1	1.3
870	1600	669	96.7	669	96.7	1.1	3.0
870	1600	855	124.2	687	98.6	1.9	4.0

JFH

TABLE 12

Tensile Properties For As-Heat Treated NASA IIB-11A

Test Temperature		Ultimate Tensile Strength		0.2% Yield Strength		Elongation (%)	Reduction of Area (%)
°C	°F	MPa	ksi	MPa	ksi	(%)	(%)
21	70	1414	205.0	1080	156.7	9.3	12.6
21	70	1372	198.7	1076	155.8	9.3	11.7
650	1200	655	95.1	655	95.1	0.4	0.0
650	1200	1023	148.4	1023	148.4	0.5	3.1
760	1400	600	87.1	600	87.1	--*	--*
760	1400	517	74.5	517	74.5	--*	--*
870	1600	290	42.4	290	42.4	--*	--*
870	1600	428	62.3	428	62.3	--*	--*

*Broke in shoulder.

1/3

TABLE 13

Tensile Properties For As-Heat Treated NASA IIB-11B

Test Temperature (°C) (°F)		Ultimate Tensile Strength MPa ksi		0.2% Yield Strength MPa ksi		Elongation (%)	Reduction of Area (%)
21	70	1572	228.4	1200	173.7	11.3	14.0
21	70	1593	230.6	1179	171.3	12.0	16.2
650	1200	1441	209.2	1103	160.4	5.0	7.3
650	1200	1462	212.4	1207	174.6	6.9	8.0
760	1400	1186	171.6	1076	156.4	1.1	5.4
760	1400	1193	172.8	1052	152.6	3.9	9.7
870	1600	821	119.4	659	95.5	1.3	0.9
870	1600	807	117.5	659	95.4	1.9	3.2

TABLE 14

Creep and Stress Rupture Properties For As-Heat Treated NASA IIb-11

<i>Test Conditions</i>	<i>C°/MPa</i>	<i>°F/ksi</i>	<i>Rupture Life (Hours)</i>	<i>Time To 0.2% Creep (Hours)</i>	<i>Elongation (%)</i>	<i>Reduction of Area (%)</i>
650/1210	1200/175		5.8	-	3.1	3.9
650/1210	1200/175		5.8	-	2.4	6.3
760/620	1400/90		103.5	-	1.6	1.5
760/620	1400/90		171.1	-	1.9	2.7
870/380	1600/55		6.7	-	0.6	2.1
870/380	1600/55		6.3	-	0.5	0.8
760/620	1400/90		-	62.0	-	-
760/620	1400/90		-	23.6	-	-

TABLE 15

Creep and Stress Rupture Properties For As-Heat Treated NASA IIb-11S

<u>Test Conditions</u>		<u>Rupture Life (Hours)</u>	<u>Time To 0.2% Creep (Hours)</u>	<u>Elongation (%)</u>	<u>Reduction of Area (%)</u>
<u>°C/MPa</u>	<u>°F/ksi</u>				
650/1210	1200/175	0.6	-	3.2	9.1
650/1210	1200/175	0.5	-	2.9	7.9
760/620	1400/90	1.2	-	0.8	-*
760/620	1400/90	77.7	-	2.0	4.2
870/380	1600/55	10.6	-	1.0	1.5
870/380	1600/55	11.0	-	0.8	0.7
760/620	1400/90	-	19.5	-	-
760/620	1400/90	-	16.0	-	-

AK
 *Broke in shoulder.

TABLE 16

Creep and Stress Rupture Properties For As-Heat Treated NASA IIB-11A

47

Test Conditions		Rupture Life (Hours)	Time To 0.2% Creep (Hours)	Elongation (%)	Reduction of Area (%)
°C/MPa	°F/ksi				
650/1210	1200/175	0	-	-	-
650/1210	1200/175	0	-	-	-
760/620	1400/90	0	-	1.0	0.6
760/620	1400/90	0	-	0.2	1.0
870/380	1600/55	0	-	0.1	1.0
870/380	1600/55	0	-	1.0	0.8
760/620	1400/90	-	0	-	-
760/620	1400/90	-	0	-	-

TABLE 17

Creep and Stress Rupture Properties For As-Heat Treated NASA IIb-11B

<i>Test Conditions</i>		<i>Rupture Life (Hours)</i>	<i>Time To 0.2% Creep (Hours)</i>	<i>Elongation (%)</i>	<i>Reduction of Area (%)</i>
<i>°C/MPa</i>	<i>°F/ksi</i>				
650/1210	1200/175	2.5	-	2.4	5.5
650/1210	1200/175	3.2	-	2.5	4.8
760/620	1400/90	44.9	-	3.0	5.5
760/620	1400/90	140.9	-	3.8	3.8
870/380	1600/55	4.1	-	1.9	2.4
870/380	1600/55	4.1	-	2.0	1.2

TABLE 18

Effect of Thermal Exposure on the 760°C (1400°F) Tensile Properties of the Task I-Series II Alloys

Alloy <u>Designation</u>	HEAT TREATED (H/T)						H/T PLUS EXPOSED					
	UTS		0.2% Y.S.		Elongation		UTS		0.2% Y.S.		Elongation	
	MPa	ksi	MPa	ksi	(%)	(%)	MPa	ksi	MPa	ksi	(%)	(%)
IIb-11	1255	182	1083	157	5.0	10.7	1186	172	979	142	1.6	2.8
IIb-11	1276	185	1096	159	5.2	10.2	1165	169	96.5	140	3.0	4.7
IIb-11S	1338	165	1083	157	2.0	2.5	1138	165	896	130	0.9	6.6
IIb-11S	1055	153	1014	147	1.1	1.3	-*	-*	-*	-*	-*	-*
IIb-11A	600	87	600	87	-**	-**	1048	152	841	122	1.8	2.8
IIb-11A	517	75	517	75	-**	-**	1048	152	848	123	1.4	9.9
IIb-11B	1186	172	1076	156	1.1	5.4	1110	161	945	137	1.5	3.8
IIb-11B	1193	173	1052	153	3.9	9.7	972	141	917	133	1.0	1.5

*Broke on loading.

**Broke on shoulder.

b/t

TABLE 19

*Effect of Thermal Exposure on the 760°C/620 MPa (1400°F/90 ksi)
Rupture Properties of the Task I - Series II Alloys*

<u>Alloy Designation</u>	<u>HEAT TREATED (H/T)</u>			<u>H/T PLUS EXPOSED</u>		
	<u>Rupture Life (Hours)</u>	<u>Elongation (%)</u>	<u>Reduction (%)</u>	<u>Rupture Life (Hours)</u>	<u>Elongation (%)</u>	<u>Reduction (%)</u>
NASA IIB-11	104	1.6	1.5	57	2.3	3.3
NASA IIB-11	171	1.9	2.7	54	2.0	2.6
NASA IIB-11S	1	0.8*	-*	73	2.6	3.8
NASA IIB-11S	78	2.0	4.2	44	2.0	2.4
NASA IIB-11A	0	1.0	0.6	3	0.8	3.5
NASA IIB-11A	0	0.2	1.0	8	1.3	4.1
NASA IIB-11B	45	3.0	5.5	27	1.5	1.3
NASA IIB-11B	141	3.8	3.8	36	2.2	2.4

*Broke in shoulder.

50

TABLE 20

Density Measurements for the Task I - Series II Alloys

<u>Alloy Designation</u>	<u>Density</u>	
	<u>g./cm.³</u>	<u>lbs./in.³</u>
NASA IIb-11	8.71	0.314
NASA IIb-11S	8.71	0.314
NASA IIb-11A	8.74	0.315
NASA IIb-11B	8.76	0.316

15

TABLE 21

Aim and Actual Chemical Analyses For Task II Powder Heats

Alloy Designation	Chemical Composition (Weight Percent) For:													
	C	Cr	Co	Mo	W	Ta	Al	Ti	Hf	V	B	Zr	O ₂	Ni
IIB-11C (AIM) KR322	0.095 0.090	8.50 8.48	9.00 9.15	2.00 1.92	7.10 7.19	6.60 6.55	4.50 4.55	0.75 0.71	1.30 1.29	0.50 0.50	0.010 0.012	0.050 0.069	Balance 70 ppm	Balance
IIB-11D (AIM) KR323	0.055 0.052	8.50 8.46	9.00 9.05	2.00 1.87	7.10 7.14	6.60 6.45	4.50 4.43	0.75 0.73	1.30 1.24	0.50 0.50	0.010 0.012	0.050 0.062	Balance 60 ppm	Balance
IIB-11E (AIM) KR324	0.055 0.055	8.50 8.55	9.00 9.05	2.00 1.90	7.10 7.14	6.60 6.37	4.50 4.45	0.75 0.72	0.70 0.70	0.50 0.51	0.010 0.013	0.050 0.043	Balance 50 ppm	Balance

59

TABLE 22

Effect of Task II Preliminary Rolling Practices on Grain Size After Solution Heat Treatment

<u>Rolling Practice*</u>	<u>Solution Treatment**</u>	<u>HIP CYCLE VARIATION ***</u>				
		<u>C</u>	<u>C1</u>	<u>C2</u>	<u>D</u>	<u>E</u>
[1]	A	7	7	6-1/2	6-1/2	6-1/2
	B	7	7	6-1/2	6	6
[2]	A	<u>W O R K A B I L I T Y</u>				
	B	<u>F A I L U R E</u>				
[3]	A	7	7	6	7	6
	B	7-1/2	7	6	5-1/2	6
[4]	A	7	7-1/2	7	7	6
	B	6-1/2	7	6-1/2	4	5

*Rolling Practice Key

- [1] Standard pass reductions from 1065°C (1950°F) with single passes between reheat.
- [2] 1245°C (2275°F)/2 hrs./RAC + [1] above.
- [3] Standard pass reductions from 1065°C (1950°F) with double passes between reheat.
- [4] Standard pass reductions from 1120°C (2050°F) with single passes between reheat.

**Solution Treatment Key

A 1230°C (2250°F)/2 hrs./RAC.
 B 1245°C (2275°F)/2 hrs./RAC.

*** See Table 2

TABLE 23

Summary of Heat Treatment Cycles for Task II Heat Treatment Evaluation

<u>Cycle Identification</u>	<u>C Y C L E</u>
[A]	1230°C (2250°F)/2 hrs/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.
[B]	1245°C (2275°F)/2 hrs/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.
[C]	1230°C (2250°F)/2 hrs/RAC + 1040°C (1900°F)/2 hrs/RAC + 760°C (1400°F)/16 hrs/AC.
[D]	1245°C (2275°F)/2 hrs/RAC + 1040°C (1900°F)/2 hrs/RAC + 760°C (1400°F)/16 hrs/AC.
[E]	1230°C (2250°F)/2 hrs/RAC + 760°C (1400°F)/64 hrs/AC.
[F]	1245°C (2275°F)/2 hrs/RAC + 955°C (1750°F)/4 hrs/RAC + 760°C (1400°F)/16 hrs/AC.
[G]	1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.
[H]	1245°C (2275°F)/2 hrs/Fast FC to 1095°C (2000°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

1/5

TABLE 24

Results of Task II Heat Treatment Evaluation for NASA IIB-11C-Preform C

<u>Heat Treatment Cycle*</u>	<u>Test Conditions**</u>	<u>Rupture Life (Hours)</u>	<u>U.T.S.</u>		<u>0.2% Y.S.</u>		<u>Elongation (%)</u>	<u>R of A (%)</u>
			<u>MPa</u>	<u>ksi</u>	<u>MPa</u>	<u>ksi</u>		
A	T: 540°C(1000°F)		1496	217	1186	172	9.1	14.0
B	T: 540°C(1000°F)		1434	208	1172	170	10.7	11.0
G	T: 540°C(1000°F)		1462	212	1103	160	11.4	11.7
A	T: 760°C(1400°F)		1324	192	1124	163	5.2	13.8
A	T: 760°C(1400°F)		1317	191	1124	163	9.3	15.4
B	T: 760°C(1400°F)		1269	184	1069	155	7.7	12.3
B	T: 760°C(1400°F)		1234	179	1096	159	2.3	7.3
A	S/R: 760°C/690MPa(1400°F/100ksi)	26					2.0	4.7
A	S/R: 760°C/690MPa(1400°F/100ksi)	21					3.2	3.6
B	S/R: 760°C/690MPa(1400°F/100ksi)	11					3.0	4.7
B	S/R: 760°C/690MPa(1400°F/100ksi)	17					1.8	5.4
C	S/R: 760°C/690MPa(1400°F/100ksi)	7					1.4	6.8
D	S/R: 760°C/690MPa(1400°F/100ksi)	1					2.0	-
A	S/R: 815°C/485MPa(1500°F/70ksi)	14					0.7	1.6
B	S/R: 815°C/485MPa(1500°F/70ksi)	13					1.4	3.2
E	S/R: 815°C/485MPa(1500°F/70ksi)	16					0.9	1.8
F	S/R: 815°C/485MPa(1500°F/70ksi)	6					0.7	4.3
G	S/R: 815°C/485MPa(1500°F/70ksi)	34					2.0	2.7
H	S/R: 815°C/485MPa(1500°F/70ksi)	28					1.4	2.4

*See Table 23 for listing.

**T indicates tensile; S/R, stress rupture.

TABLE 25

Results of Task II Heat Treatment Evaluation for NASA IIb-11C-Preform Cl

<u>Heat Treatment Cycle*</u>	<u>Test Conditions**</u>	<u>Rupture Life (Hours)</u>	<u>U.T.S.</u> MPa	<u>U.T.S.</u> ksi	<u>0.2% Y.S.</u> MPa	<u>0.2% Y.S.</u> ksi	<u>Elongation (%)</u>	<u>R of A (%)</u>
A	T: 540°C(1000°F)		1496	217	1117	162	9.3	13.8
B	T: 540°C(1000°F)		1420	206	1110	161	9.8	13.3
G	T: 540°C(1000°F)		1448	210	1083	157	11.4	13.8
A	T: 760°C(1400°F)		1262	183	1103	160	6.4	11.8
A	T: 760°C(1400°F)		1276	185	1089	158	5.2	10.7
B	T: 760°C(1400°F)		1296	188	1110	161	5.2	7.0
B	T: 760°C(1400°F)		1200	174	1124	163	4.5	8.3
TG	S/R: 760°C/690MPa(1400°F/100ksi)	30					1.8	5.4
	S/R: 760°C/690MPa(1400°F/100ksi)	29					3.0	3.8
	S/R: 760°C/690MPa(1400°F/100ksi)	25					1.6	4.3
	S/R: 760°C/690MPa(1400°F/100ksi)	19					2.3	4.7
A	S/R: 815°C/485MPa(1500°F/70ksi)	14					0.2	0
B	S/R: 815°C/485MPa(1500°F/70ksi)	13					1.4	0
E	S/R: 815°C/485MPa(1500°F/70ksi)	17					-	-
F	S/R: 815°C/485MPa(1500°F/70ksi)	4					1.1	1.7
G	S/R: 815°C/485MPa(1500°F/70ksi)	20					2.0	5.0
H	S/R: 815°C/485MPa(1500°F/70ksi)	24					3.2	2.8

*See Table 23 for listing.

**T indicates tensile; S/R, stress rupture.

TABLE 26

Results of Task II Heat Treatment Evaluation for NASA IIB-11C-Preform C2

<u>Heat Treatment Cycle*</u>	<u>Test Conditions**</u>	<u>Rupture Life (Hours)</u>	<u>U.T.S</u>		<u>0.2% Y.S.</u>		<u>Elongation (%)</u>	<u>R of A (%)</u>
			<u>MPa</u>	<u>ksi</u>	<u>MPa</u>	<u>ksi</u>		
A	T: 540°C(1000°F)		1469	213	1145	166	10.0	16.5
B	T: 540°C(1000°F)		1407	204	1055	153	8.9	13.8
G	T: 540°C(1000°F)		1441	209	1089	158	11.1	16.8
A	T: 760°C(1400°F)		1317	191	1117	162	6.4	14.0
A	T: 760°C(1400°F)		1317	191	1131	164	5.7	9.2
B	T: 760°C(1400°F)		1317	191	1165	169	2.7	5.7
B	T: 760°C(1400°F)		1310	190	1138	165	4.5	4.0
UR 17	S/R: 760°C/690MPa(1400°F/100ksi)	33					3.0	4.0
	S/R: 760°C/690MPa(1400°F/100ksi)	33					3.4	5.7
	S/R: 760°C/690MPa(1400°F/100ksi)	27					2.5	4.5
	S/R: 760°C/690MPa(1400°F/100ksi)	25					2.5	4.1
A	S/R: 815°C/485MPa(1500°F/70ksi)	19					0.9	1.9
B	S/R: 815°C/485MPa(1500°F/70ksi)	14					2.7	2.1
E	S/R: 815°C/485MPa(1500°F/70ksi)	24					0.9	0.8
F	S/R: 815°C/485MPa(1500°F/70ksi)	9					0.5	1.2
G	S/R: 815°C/485MPa(1500°F/70ksi)	30					2.3	3.4
H	S/R: 815°C/485MPa(1500°F/70ksi)	35					2.3	3.3

*See Table 23 for listing.

**T indicates tensile; S/R stress rupture.

TABLE 27

Results of Task II Heat Treatment Evaluation for NASA IIB-11D-Preform D

<u>Heat Treatment Cycle*</u>	<u>Test Conditions**</u>	<u>Rupture Life (Hours)</u>	<u>U.T.S.</u>		<u>0.2% Y.S.</u>		<u>Elongation (%)</u>	<u>R of A (%)</u>
			<u>MPa</u>	<u>ksi</u>	<u>MPa</u>	<u>ksi</u>		
A	T: 540°C (1000°F)		1503	218	1138	165	11.4	11.6
B	T: 540°C (1000°F)		1427	207	1131	164	9.1	15.5
G	T: 540°C (1000°F)		1413	205	1062	154	10.7	18.2
A	T: 760°C (1400°F)		1276	185	1062	154	9.1	13.3
A	T: 760°C (1400°F)		1276	185	1083	157	8.9	11.6
B	T: 760°C (1400°F)		1303	189	1110	161	7.3	10.6
B	T: 760°C (1400°F)		1289	187	1089	158	6.8	10.4
F	T: 760°C (1400°F)		1214	176	1117	162	2.7	5.1
G	T: 760°C (1400°F)		1220	177	1076	156	14.3	19.3
A	S/R: 760°C/690MPa (1400°F/100ksi)	79					4.5	6.3
A	S/R: 760°C/690MPa (1400°F/100ksi)	78					3.4	4.4
B	S/R: 760°C/690MPa (1400°F/100ksi)	96					2.5	3.4
B	S/R: 760°C/690MPa (1400°F/100ksi)	60					3.2	5.3
A	S/R: 815°C/485MPa (1500°F/70ksi)	23					2.3	1.3
B	S/R: 815°C/485MPa (1500°F/70ksi)	39					4.3	0.8
E	S/R: 815°C/485MPa (1500°F/70ksi)	39					0.7	0.8
F	S/R: 815°C/485MPa (1500°F/70ksi)	8					0.9	0.6
G	S/R: 815°C/485MPa (1500°F/70ksi)	79					3.6	3.7
H	S/R: 815°C/485MPa (1500°F/70ksi)	67					2.3	4.0

*See Table 23 for listing.

**T indicates tensile; S/R, stress rupture.

TABLE 28

Results of Task II Heat Treatment Evaluation for NASA IIB-11E-Preform E

<u>Heat Treatment Cycle*</u>	<u>Test Conditions**</u>	<u>Rupture Life (Hours)</u>	<u>U.T.S.</u>		<u>0.2% Y.S.</u>		<u>Elongation (%)</u>	<u>R of A (%)</u>
			<u>MPa</u>	<u>ksi</u>	<u>MPa</u>	<u>ksi</u>		
A	T: 540°C(1000°F)		1372	199	1117	162	8.6	15.5
B	T: 540°C(1000°F)		1338	194	1110	161	6.4	10.9
G	T: 540°C(1000°F)		1358	197	1069	155	11.8	19.0
A	T: 760°C(1400°F)		1269	184	1096	159	6.6	11.0
A	T: 760°C(1400°F)		1289	187	1089	158	10.9	17.9
B	T: 760°C(1400°F)		1310	190	1131	164	8.9	11.5
B	T: 760°C(1400°F)		1289	187	1069	155	13.6	18.2
H	T: 760°C(1400°F)		1234	179	1000	145	16.4	24.0
<i>b5</i>								
A	S/R: 760°C/690MPa(1400°F/100ksi)	77					2.7	5.2
A	S/R: 760°C/690MPa(1400°F/100ksi)	55					2.5	5.8
B	S/R: 760°C/690MPa(1400°F/100ksi)	55					3.6	4.5
B	S/R: 760°C/690MPa(1400°F/100ksi)	59					3.0	2.8
A	S/R: 815°C/485MPa(1500°F/70ksi)	39					1.1	1.4
B	S/R: 815°C/485MPa(1500°F/70ksi)	42					1.4	2.4
E	S/R: 815°C/485MPa(1500°F/70ksi)	11					0.9	2.0
F	S/R: 815°C/485MPa(1500°F/70ksi)	53					2.5	2.0
G	S/R: 815°C/485MPa(1500°F/70ksi)	76					3.2	4.3
H	S/R: 815°C/485MPa(1500°F/70ksi)	62					3.6	4.2

*See Table 23 for listing.

**T indicates tensile; S/R, stress rupture.

TABLE 29

Results of X-Ray Phase Analyses for Task II Disks in the
Heat Treated and Heat Treated Plus Exposed Condition

<u>Alloy Designation</u>	<u>Preform Identity</u>	<u>Material Condition**</u>	<u>Relative Concentration* of Phases Present</u>			
			<u>MC</u>	<u>M₆C</u>	<u>M₂₃C₆</u>	<u>M₄</u>
<i>IIIb-11C</i>	C	H/T	VS	W	VW	
<i>IIIb-11C</i>	C	H/T + Exposed	S	S	W	W
<i>IIIb-11C</i>	C1	H/T	VS	W	VW	
<i>IIIb-11C</i>	C1	H/T + Exposed	S	S	W	W
<i>IIIb-11C</i>	C2	H/T	VS	W	VW	
<i>IIIb-11C</i>	C2	H/T + Exposed	S	S	W	W
<i>IIIb-11D</i>	D	H/T	VS	W	VW	
<i>IIIb-11D</i>	D	H/T + Exposed	S	S	W	W
<i>IIIb-11E</i>	E	H/T	VS	W	VW	
<i>IIIb-11E</i>	E	H/T + Exposed	S	S	W	

*S represents Strong; M, Moderate; W, Weak; and V, Very

**H/T indicates Heat Treated (detail below); Exposed indicates 870°C (1600°F)/1500 hours.

All Alloys: 1245°C (2275°F)/2 hours/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hours/RAC + 760°C (1400°F)/16 hours/AC.

TABLE 30

Tensile Properties of NASA IIb-11C Disk Fabricated From HIP Preform C

<u>Test Temperature (°C)</u>	<u>Temperature (°F)</u>	<u>Ultimate Tensile Strength MPa</u>	<u>ksi</u>	<u>0.2% Yield Strength MPa</u>	<u>ksi</u>	<u>Elongation (%)</u>	<u>Reduction Of Area (%)</u>
21	70	1477	214.2	1102	159.8	10.7	14.3
21	70	1449	210.1	1108	160.7	10.0	15.1
540	1000	1460	211.8	1069	155.0	11.4	18.0
540	1000	1463	212.4	1104	160.3	11.4	11.7
650	1200	1447	209.9	1085	157.3	12.7	17.7
650	1200	1429	207.3	1074	155.8	10.7	15.9
760	1400	1204	174.6	1035	150.1	6.4	12.5
760	1400	1235	179.1	1124	163.0	7.7	8.6
815	1500	1022	148.2	976	141.6	4.5	9.1
815	1500	1088	157.9	936	135.7	6.4	6.3

Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 31

Tensile Properties of NASA IIb-11C Disk Fabricated From HIP Preform Cl

<u>Test Temperature (°C)</u>	<u>Temperature (°F)</u>	<u>Ultimate Tensile Strength MPa</u>	<u>ksi</u>	<u>0.2% Yield Strength MPa</u>	<u>ksi</u>	<u>Elongation (%)</u>	<u>Reduction Of Area (%)</u>
21	70	1482	215.0	1089	158.0	10.0	14.3
21	70	1472	213.5	1064	154.3	11.6	15.0
540	1000	1463	212.2	1105	160.2	13.0	16.7
540	1000	1451	210.4	1079	156.5	11.4	13.8
650	1200	1440	208.9	1070	155.2	13.6	17.4
650	1200	1418	205.7	1071	155.3	12.3	16.0
760	1400	1234	178.9	1085	157.3	8.2	10.3
760	1400	1242	180.1	1079	156.5	12.5	16.6
760	1400	1201	174.2	1123	162.9	4.5	8.3
815	1500	1089	157.9	954	138.4	5.9	8.3
815	1500	1092	158.4	929	134.7	7.7	11.1

LJ
 Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 32

Tensile Properties of NASA IIb-11C Disk Fabricated From HIP Preform C2

<u>Test Temperature</u> <u>°C</u>	<u>Temperature</u> <u>°F</u>	<u>Ultimate Tensile Strength</u> <u>MPa</u>	<u>ksi</u>	<u>0.2% Yield Strength</u> <u>MPa</u>	<u>ksi</u>	<u>Elongation</u> <u>(%)</u>	<u>Reduction of</u> <u>Area (%)</u>
21	70	1538	223.1	1088	157.8	13.4	13.5
21	70	1436	208.2	1107	160.6	10.5	8.8
540	1000	1429	207.2	1086	157.5	13.0	16.0
540	1000	1444	209.4	1087	157.7	11.1	16.8
650	1200	1404	203.6	1012	146.8	12.5	15.3
650	1200	1393	202.0	1034	150.0	11.6	17.7
760	1400	1219	176.8	1045	151.5	9.3	13.7
760	1400	1230	178.4	1049	152.1	13.2	14.4
815	1500	1075	155.9	931	135.0	7.3	9.0
815	1500	1090	158.1	938	136.1	6.4	13.6

EB
Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 33

Tensile Properties of NASA IIb-11D Disk Fabricated From HIP Preform D

<u>Test Temperature (°C)</u>	<u>(°F)</u>	<u>Ultimate Tensile Strength MPa</u>	<u>ksi</u>	<u>0.2% Yield Strength MPa</u>	<u>ksi</u>	<u>Elongation (%)</u>	<u>Reduction of Area (%)</u>
21	70	1441	209.0	1067	154.7	11.6	17.4
21	70	1481	214.8	1100	159.5	12.3	14.6
540	1000	1225	177.7	1054	152.8	5.7	12.9
540	1000	1415	205.2	1059	153.6	10.7	18.2
650	1200	1391	201.7	1058	153.5	8.2	11.0
650	1200	1369	198.6	1060	153.8	8.9	17.8
760	1400	1234	179.0	1025	148.7	14.1	23.5
760	1400	1223	177.4	1025	148.7	10.7	20.6
760	1400	1219	176.8	1074	155.7	14.3	19.3
815	1500	1105	160.2	971	140.9	10.5	20.0
815	1500	1078	156.4	945	137.1	11.6	18.3

Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 34

Tensile Properties of NASA IIb-11E Disk Fabricated From HIP Preform E

<u>Test Temperature</u> <u>(°C)</u>	<u>Temperature</u> <u>(°F)</u>	<u>Ultimate Tensile Strength</u> <u>MPa</u>	<u>ksi</u>	<u>0.2% Yield Strength</u> <u>MPa</u>	<u>ksi</u>	<u>Elongation</u> <u>(%)</u>	<u>Reduction of Area (%)</u>
21	70	1477	214.4	1098	159.3	13.2	17.7
21	70	1491	216.4	1091	158.3	13.0	16.9
540	1000	1369	198.8	1034	150.0	13.0	15.7
540	1000	1359	197.2	1071	155.4	11.8	19.0
650	1200	1344	195.0	1027	149.0	10.9	15.8
650	1200	1323	192.0	1002	145.5	10.0	19.7
760	1400	1229	178.4	1000	145.2	18.6	25.9
760	1400	1233	179.0	1045	151.6	17.0	23.9
815	1500	1088	157.9	954	138.4	16.4	25.7
815	1500	1096	159.1	972	141.1	18.9	22.9

Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 35

Stress Rupture Properties of NASA IIb-11C Disk Fabricated From HIP Preform C

Test Conditions		Rupture Life (Hours)	Elongation (%)	Reduction of Area (%)
°C/MPa	°F/ksi			
650/1103	1200/160	39.4	5.9	9.8
650/1103	1200/160	42.2	8.0	14.6
760/690	1400/100	41.8	1.1	5.5
760/690	1400/100	35.1	1.4	6.0
815/483	1500/70	22.8	1.1	5.3
815/483	1500/70	34.1	2.0	2.7
870/345	1600/50	6.3	0.9	2.2
870/345	1600/50	5.4	1.1	3.8

Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 36

Stress Rupture Properties of NASA IIb-11C Disk Fabricated From HIP Preform C1

<u>Test Conditions</u>		<u>Rupture Life (Hours)</u>	<u>Elongation (%)</u>	<u>Reduction of Area (%)</u>
<u>°C/MPa</u>	<u>°F/ksi</u>			
650/1103	1200/160	44.0	4.8	10.5
650/1103	1200/160	38.4	6.6	14.0
760/690	1400/100	30.1	3.4	4.2
760/690	1400/100	43.0	2.3	3.8
815/483	1500/70	28.6	2.0	3.3
815/483	1500/70	19.5	2.0	5.0
870/345	1600/50	7.7	1.4	3.9
870/345	1600/50	7.3	1.6	1.8

LJ
 Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 37

Stress Rupture Properties of NASA IIb-11C Disk Fabricated From HIP Preform C2

<u>Test Conditions</u>		<u>Rupture Life</u>	<u>Elongation</u>	<u>Reduction of</u>
<u>°C/MPa</u>	<u>°F/ksi</u>	<u>(Hours)</u>	<u>(%)</u>	<u>Area (%)</u>
650/1103	1200/160	28.8	5.5	10.5
650/1103	1200/160	25.1	8.6	14.7
760/690	1400/100	50.2	4.1	3.9
760/690	1400/100	50.4	2.7	3.8
815/483	1500/70	26.0	1.1	3.2
815/483	1500/70	30.2	2.3	3.4
870/345	1600/50	6.7	1.8	1.6
870/345	1600/50	5.8	1.4	1.4

89
Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/
RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 38

Stress Rupture Properties of NASA IIB-11D Disk Fabricated From HIP Preform D

Test Conditions		Rupture Life (Hours)	Elongation (%)	Reduction of Area (%)
°C/MPa	°F/ksi			
650/1103	1200/160	87.9	11.1	18.0
650/1103	1200/160	91.6	12.3	19.8
760/690	1400/100	106.9	5.0	8.8
760/690	1400/100	84.0	4.8	8.0
815/483	1500/70	92.8	1.8	3.6
815/483	1500/70	79.1	3.6	3.7
870/345	1600/50	26.1	2.3	2.0
870/345	1600/50	27.0	2.3	2.7

Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 39

Stress Rupture Properties of NASA IIB-11E Disk Fabricated From HIP Preform E

Test Conditions		Rupture Life (Hours)	Elongation (%)	Reduction of Area (%)
°C/MPa	°F/ksi			
650/1103	1200/160	59.1	13.6	20.1
650/1103	1200/160	67.7	14.3	20.7
760/690	1400/100	138.9	2.5	6.9
760/690	1400/100	136.2	5.0	7.1
815/483	1500/70	99.6	4.1	4.7
815/483	1500/70	75.9	3.2	4.3
870/345	1600/50	86.3	2.0	2.7
870/345	1600/50	48.8	4.8	4.2

Heat Treatment: 1245°C (2275°F)/2 hrs/Slow FC to 1150°C (2100°F)/RAC + 870°C (1600°F)/16 hrs/RAC + 760°C (1400°F)/16 hrs/AC.

TABLE 40

Effect of Thermal Exposure on the 760°C (1400°F) Tensile Properties of the Task II Compositions

Alloy Designation	Preform Identity	HEAT TREATED (H/T)						H/T PLUS EXPOSED					
		UTS		0.2% Y.S.		Elongation		UTS		0.2% Y.S.		Elongation	
		MPa	ksi	MPa	ksi	(%)	(%)	MPa	ksi	MPa	ksi	(%)	(%)
IIb-11C	C	1204	175	1035	150	6.4	12.5	979	142	779	113	3.2	6.0
IIb-11C	C	1234	179	1124	163	7.7	8.6	938	136	772	112	2.7	3.8
IIb-11C	C1	1234	179	1085	157	8.2	10.3	952	138	793	115	2.7	4.2
IIb-11C	C1	1242	180	1085	157	12.5	16.6	979	142	772	112	3.0	6.0
IIb-11C	C2	1219	177	1049	152	9.3	13.7	917	133	738	107	3.6	7.0
IIb-11C	C2	1230	178	1049	152	13.2	14.4	952	138	745	108	2.3	2.9
IIb-11D	D	1234	179	1025	149	14.1	23.5	1020	148	745	108	4.1	11.8
IIb-11D	D	1223	177	1025	149	10.7	20.6	1025	149	745	108	5.0	9.7
IIb-11E	E	1230	178	1000	145	18.6	25.9	1035	150	821	119	6.0	13.2
IIb-11E	E	1234	179	1049	152	17.0	23.9	1025	149	869	126	8.0	11.2

12

TABLE 41

*Effect of Thermal Exposure on the 760°C/690 MPa (1400°F/100 ksi)
Rupture Properties of the Task II Compositions*

<u>Alloy Designation</u>	<u>Preform Identity</u>	<u>HEAT TREATED (H/T)</u>			<u>H/T PLUS EXPOSED</u>		
		<u>Rupture Life (Hours)</u>	<u>Elongation (%)</u>	<u>Reduction (%)</u>	<u>Rupture Life (Hours)</u>	<u>Elongation (%)</u>	<u>Reduction (%)</u>
<i>IIb-11C</i>	C	42	1.1	5.5	6	1.8	3.2
<i>IIb-11C</i>	C	35	1.4	6.0	5	1.8	4.8
<i>IIb-11C</i>	C1	30	3.4	4.2	5	2.5	3.0
<i>IIb-11C</i>	C1	43	2.3	3.8	4	2.7	3.3
<i>IIb-11C</i>	C2	50	4.1	3.9	3	2.0	6.0
<i>IIb-11C</i>	C2	50	2.7	3.8	8	1.6	5.2
<i>IIb-11D</i>	D	107	5.0	8.8	6	2.3	2.2
<i>IIb-11D</i>	D	84	4.8	8.0	10	3.6	9.0
<i>IIb-11E</i>	E	139	2.5	6.9	13	4.8	9.1
<i>IIb-11E</i>	E	136	5.0	7.1	17	7.3	8.5

7/

TABLE 42

Density Measurements for the Task II Compositions

<u>Alloy Designation</u>	<u>Preform Identity</u>	<u>Density</u>	
		<u>g/cm³</u>	<u>lbs/in³</u>
IIb-11C	C	8.76	0.316
IIb-11C	C1	8.76	0.316
IIb-11C	C2	8.76	0.316
IIb-11D	D	8.79	0.317
IIb-11E	E	8.75	0.316

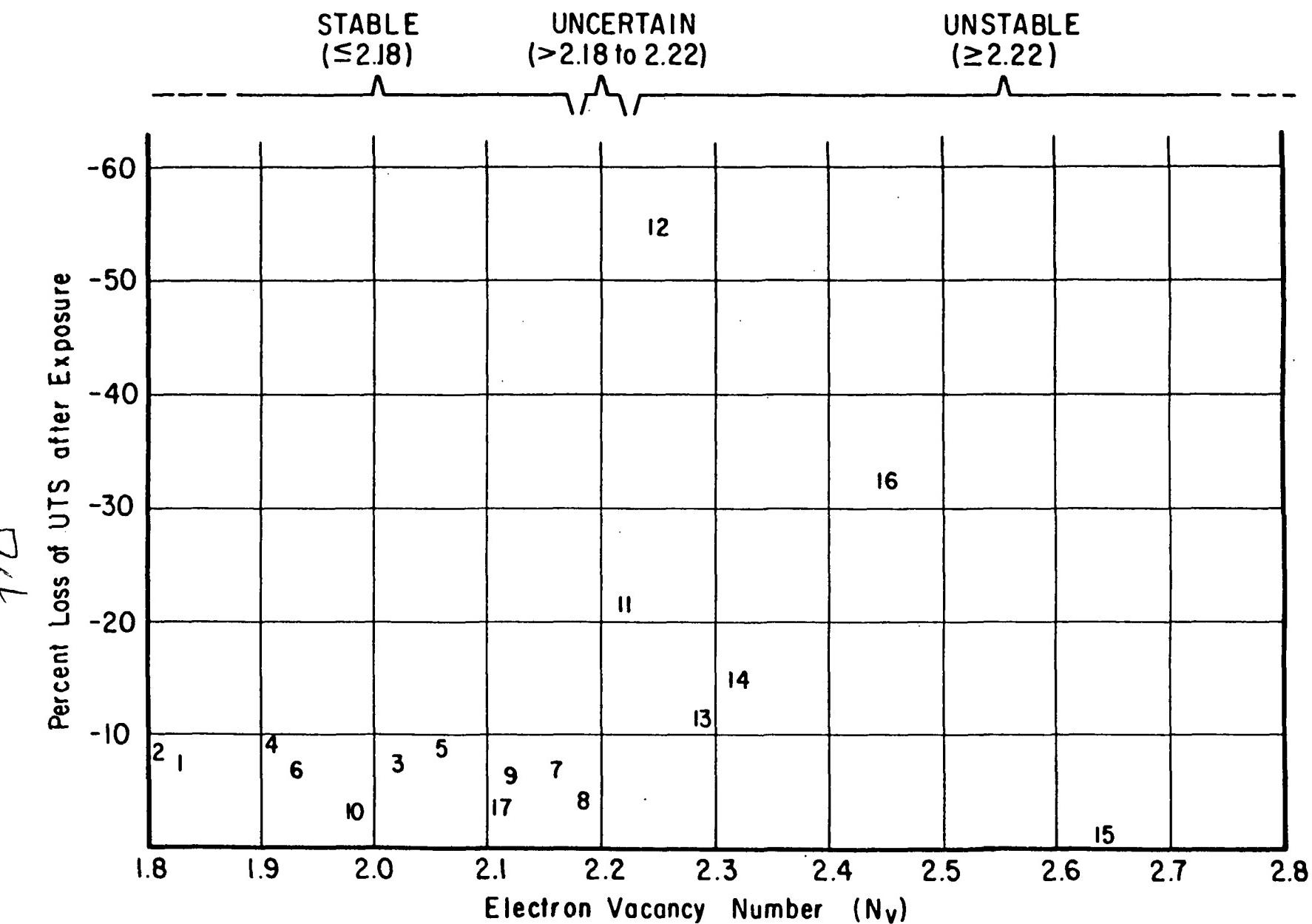


FIGURE 1 : CHART ILLUSTRATING THERMAL STABILITY LIMITS WITHIN THE NASA IIb ALLOY SYSTEM.

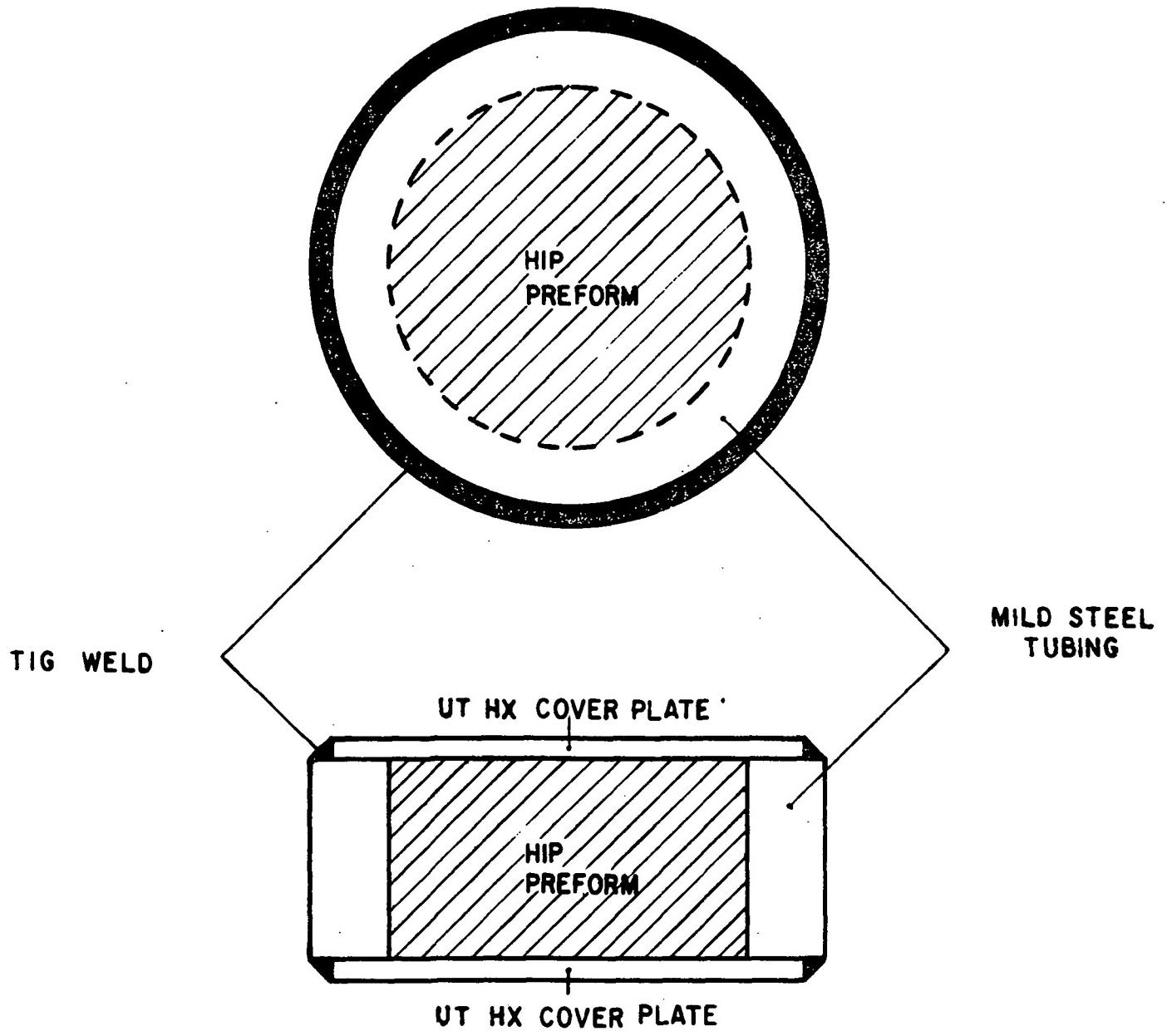
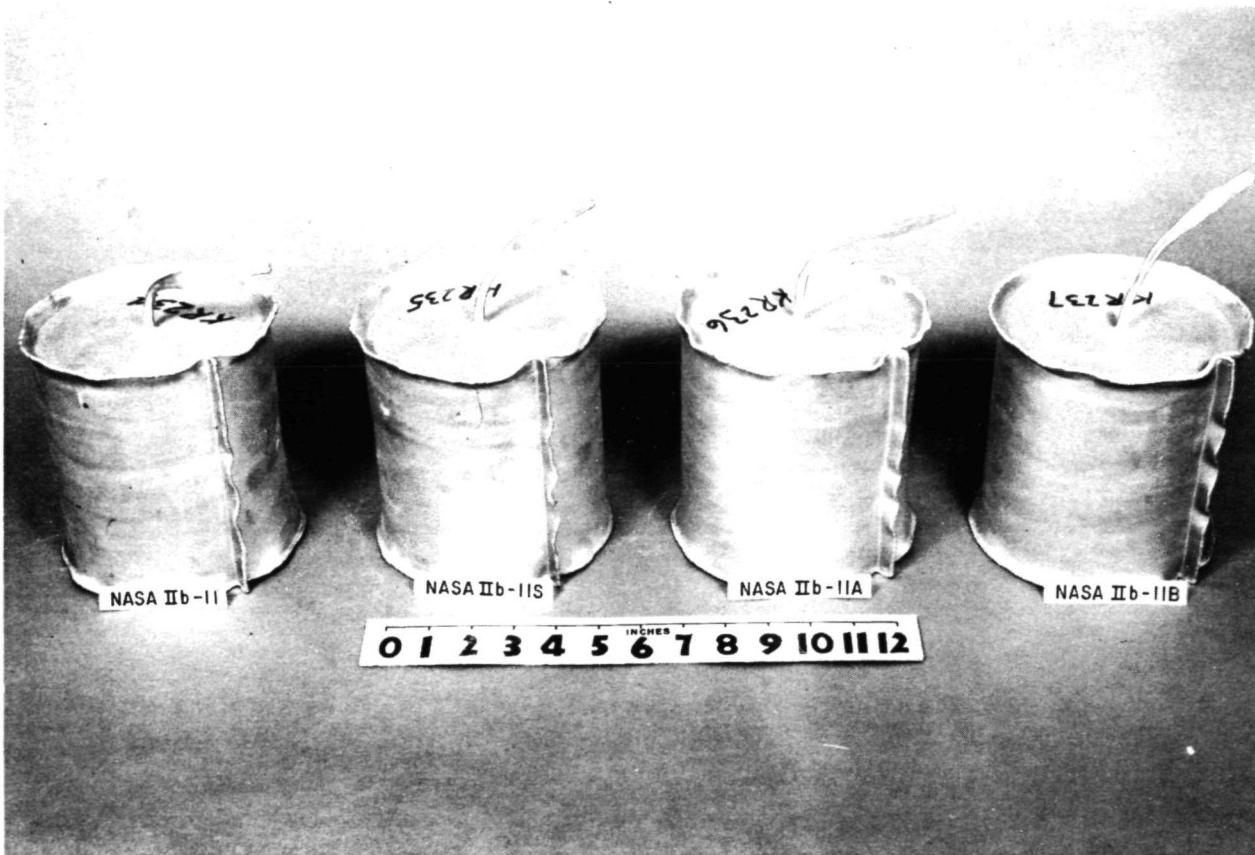


FIGURE 2 : SCHEMATIC OF CANNING PROCEDURE
PRIOR TO CROSS ROLLING

REPRODUCIBILITY OF THIS
ORIGINAL PAGE IS POOR



M 5492

FIGURE 3: GENERAL APPEARANCE OF TASK I -
SERIES I HOT ISOSTATICALLY PRESSED
PREFORMS.

76

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

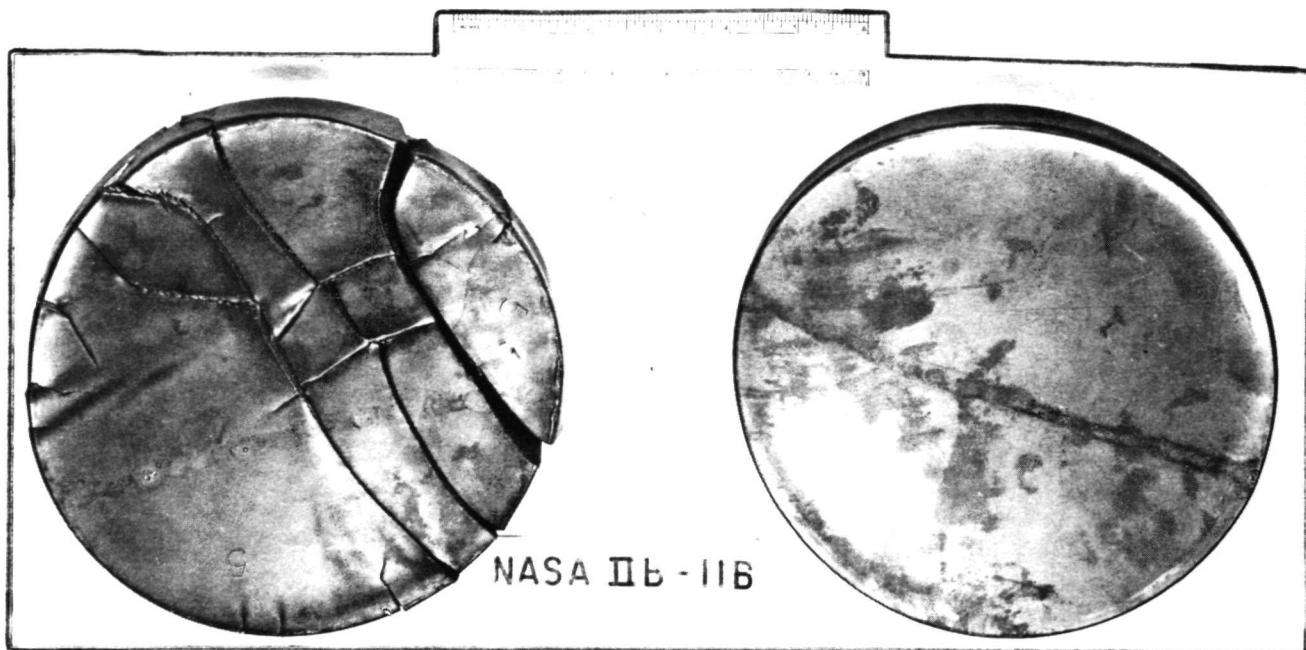


FIGURE 4: GENERAL APPEARANCE OF TASK I-SERIES I
NASA II_b-II_B DISKS AFTER CROSS ROLLING.



125 X



250 X



500 X

FIGURE 5 : SCANNING ELECTRON MICROGRAPHS ILLUSTRATING WORKABILITY FAILURE DURING CROSS ROLLING DUE TO INADEQUATE PARTICLE COMPACTION.

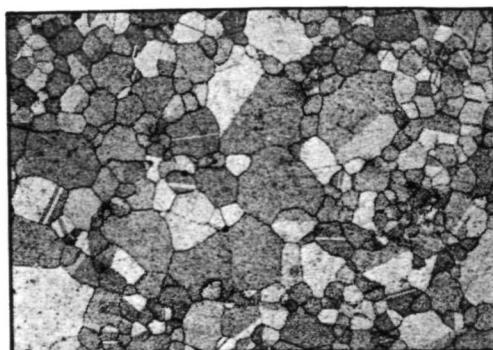
78

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR



FIGURE 6 : APPEARANCE OF TASK I - SERIES II DISKS AFTER CROSS ROLLING .

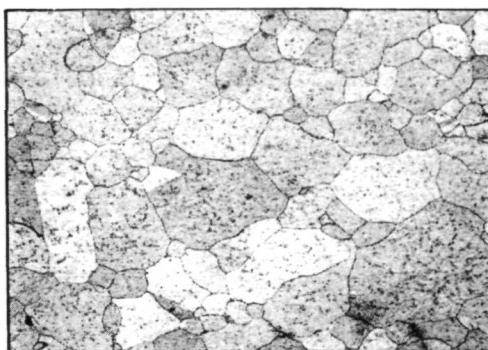


200X

NASA IIb-II : 1230°C(2250°F)/4 hrs/RAC + 1040°C(1900°F)/2 hrs/RAC +
760°C(1400°F)/16 hrs/AC

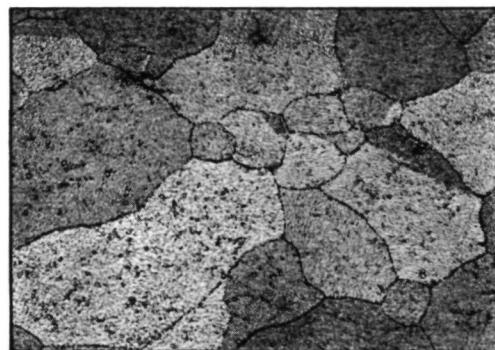


500X

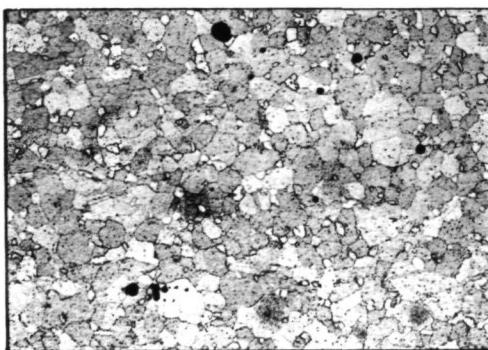


200X

NASA IIb-IIIS : 1230°C(2250°F)/4 hrs/RAC + 1040°C(1900°F)/2 hrs/RAC +
760°C(1400°F)/16 hrs/AC

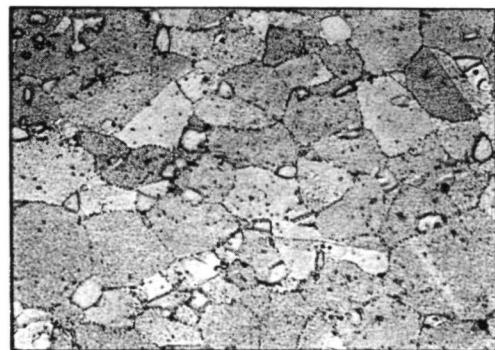


500X

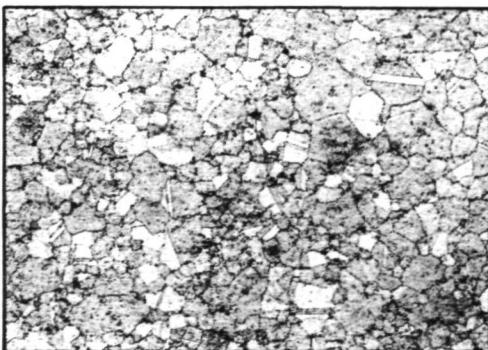


200X

NASA IIb-IIIA : 1220°C(2225°F)/60 hrs/RAC + 1040°C(1900°F)/2 hrs/RAC +
760°C(1400°F)/16 hrs/AC

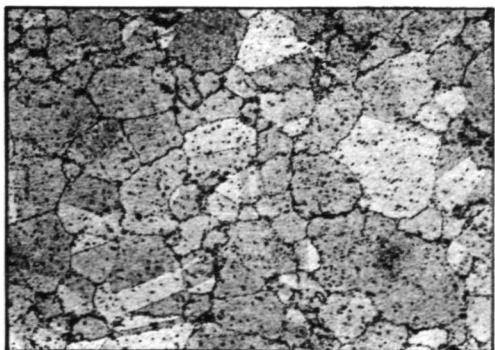


500X



200X

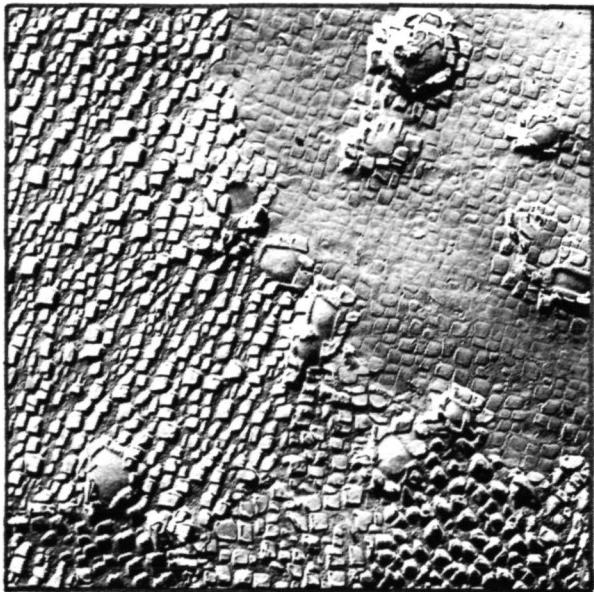
NASA IIb-IIIB : 1245°C(2275°F)/2 hrs/RAC + 1040°C(1900°F)/2 hrs/RAC +
760°C(1400°F)/16 hrs/AC



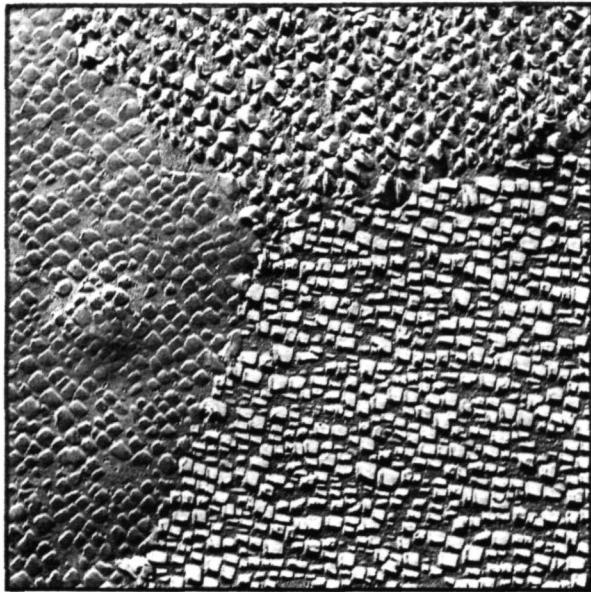
500X

Fig. 7 : OPTICAL MICROGRAPHS REPRESENTING TASK I - SERIES II
DISKS HEAT TREATED BY OPTIMUM METHOD

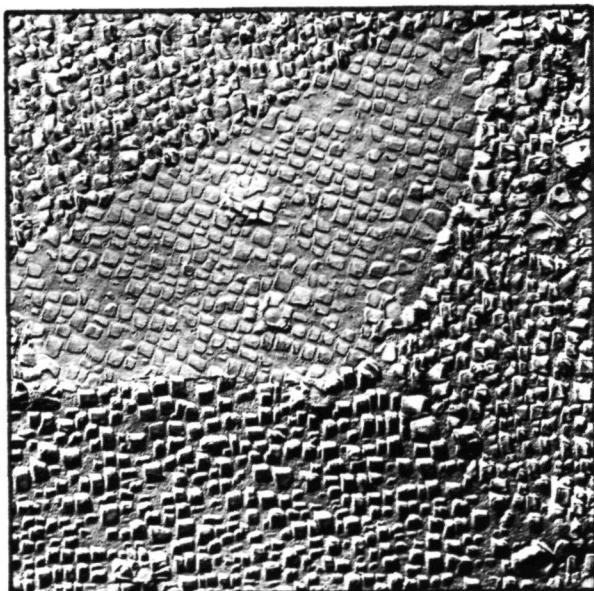
80



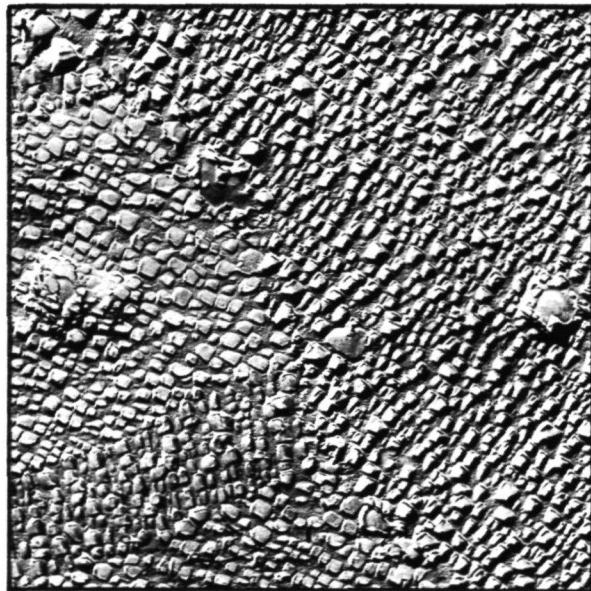
EM 5363



EM 5369



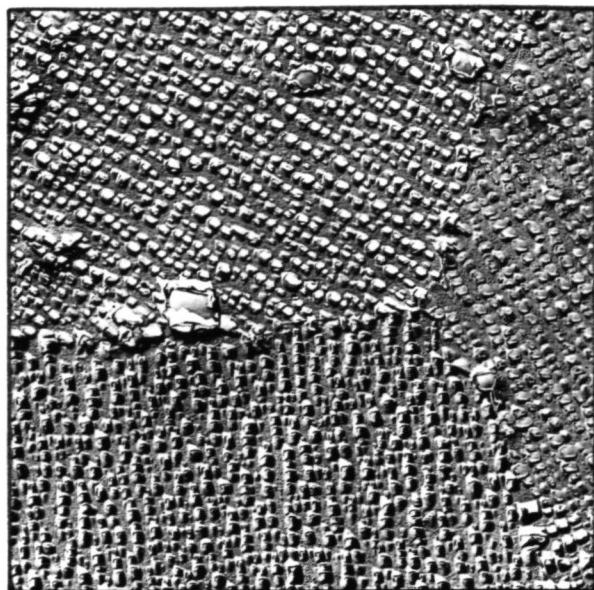
EM 5368



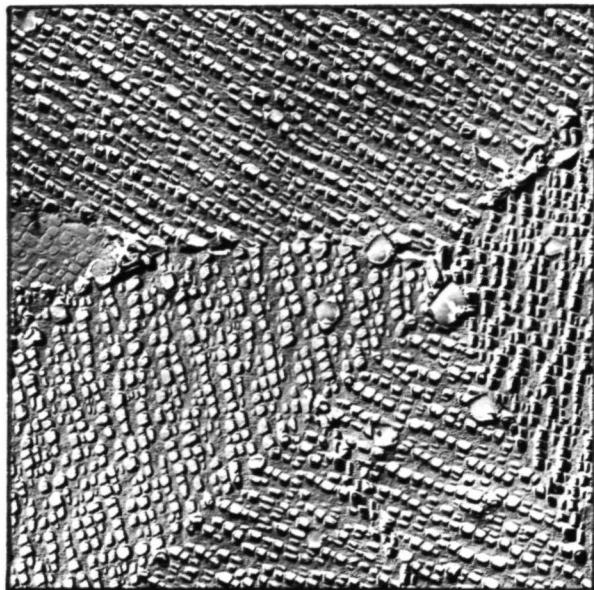
EM 5365

Fig 8 : ELECTRON MICROGRAPHS OF NASA IIb-II
IN AS - HEAT TREATED CONDITION

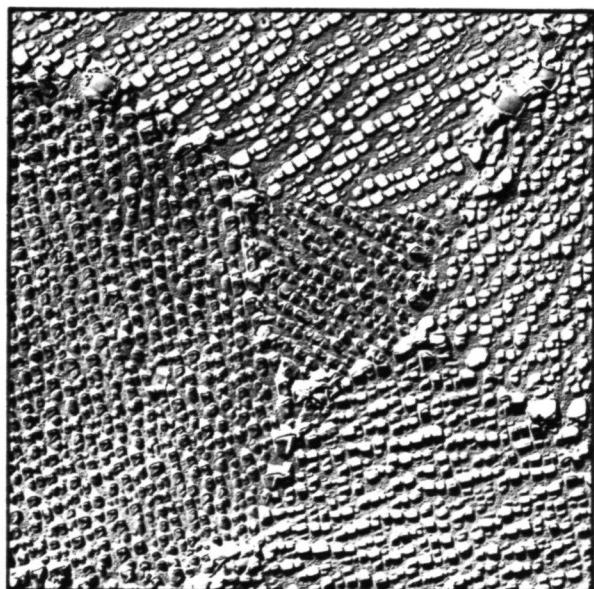
Mag. : 6000X



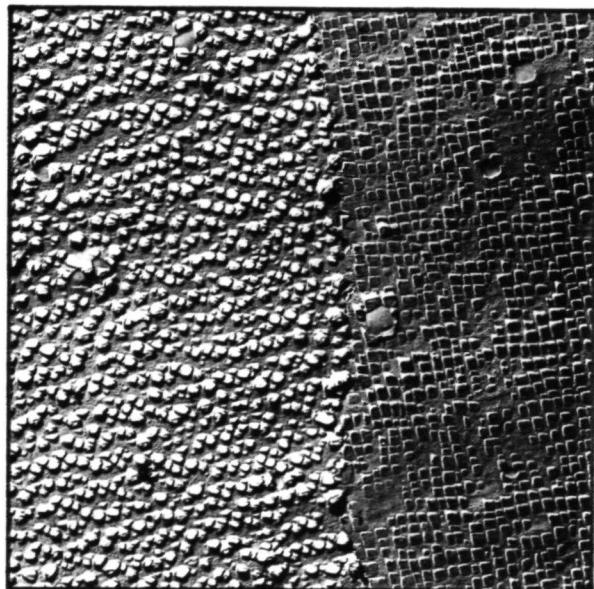
EM5362



EM5358



EM5359

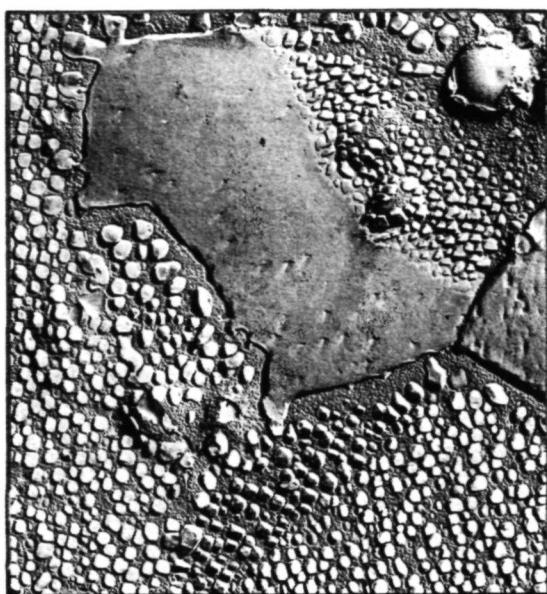


EM5356

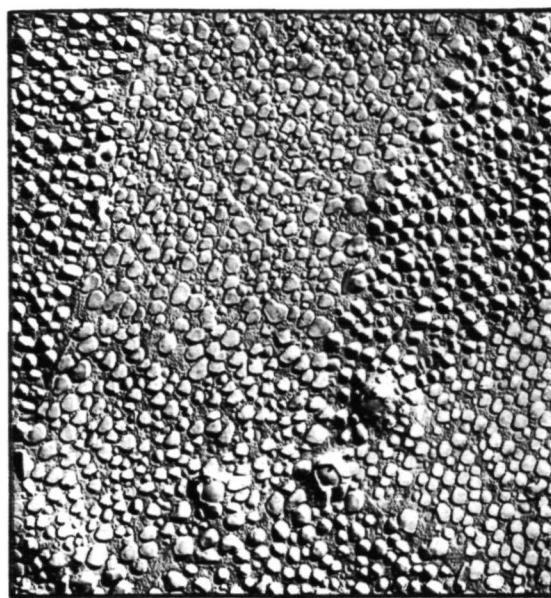
Fig 9: ELECTRON MICROGRAPHS OF NASA IIb-IIS
IN AS-HEAT TREATED CONDITION

Mag. : 6000X

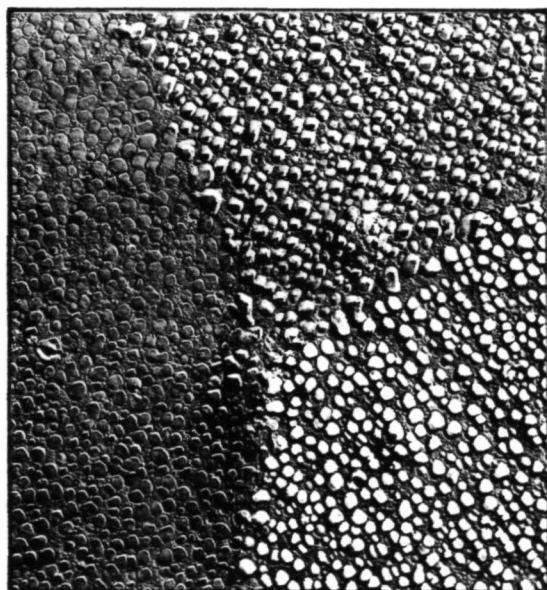
85



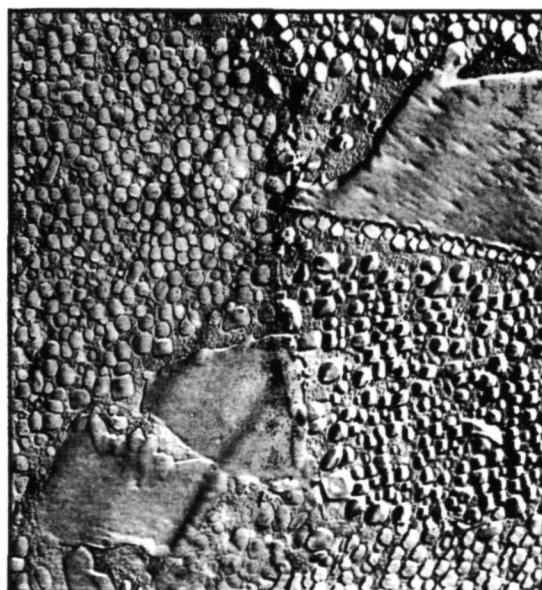
EM5355



EM5350



EM5353

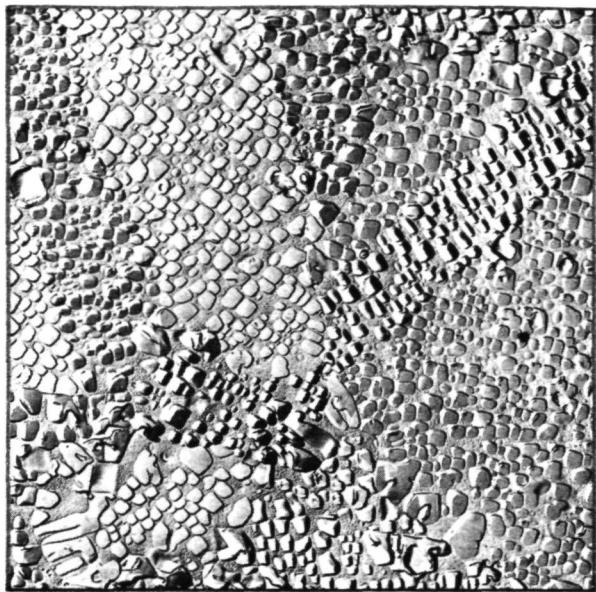


EM5349

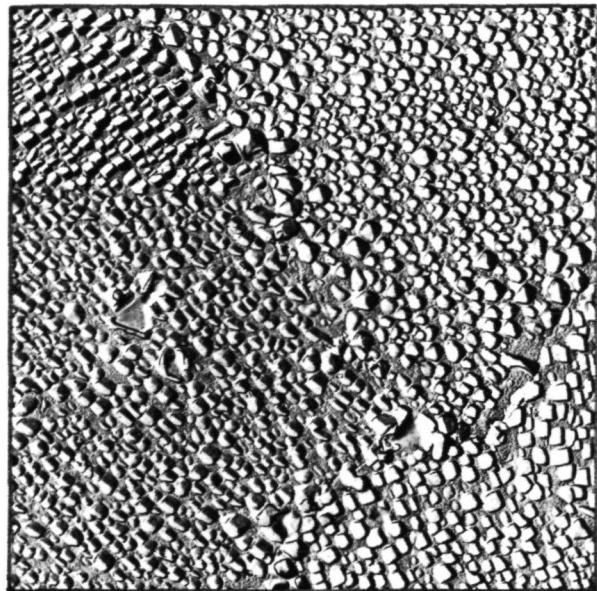
Fig. 10 : ELECTRON MICROGRAPHS OF NASA IIb-IIA
IN AS- HEAT TREATED CONDITION

Mag. : 6000X

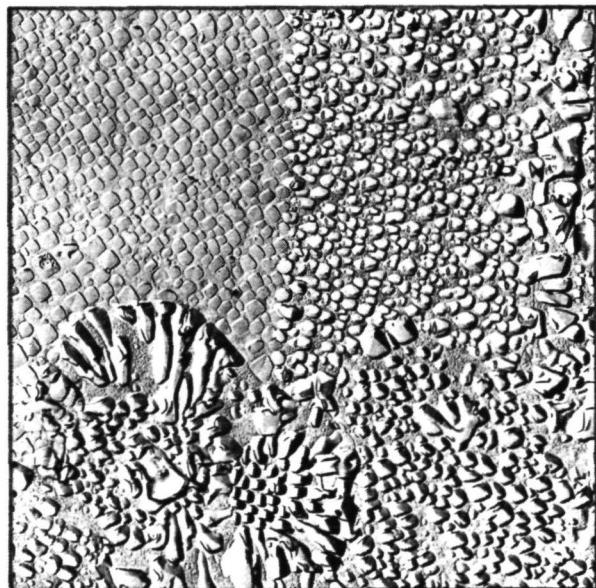
83



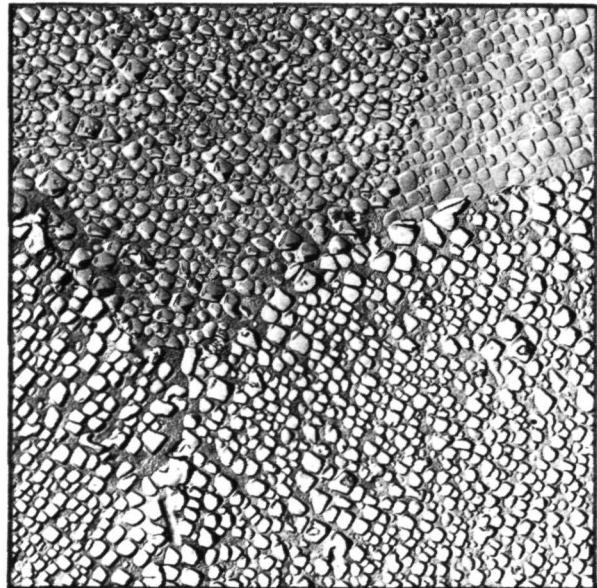
EM5348



EM5342



EM5347



EM5346

Fig. II : ELECTRON MICROGRAPHS OF NASA IIb-IIb
IN AS-HEAT TREATED CONDITION

84

Mag. : 6000X

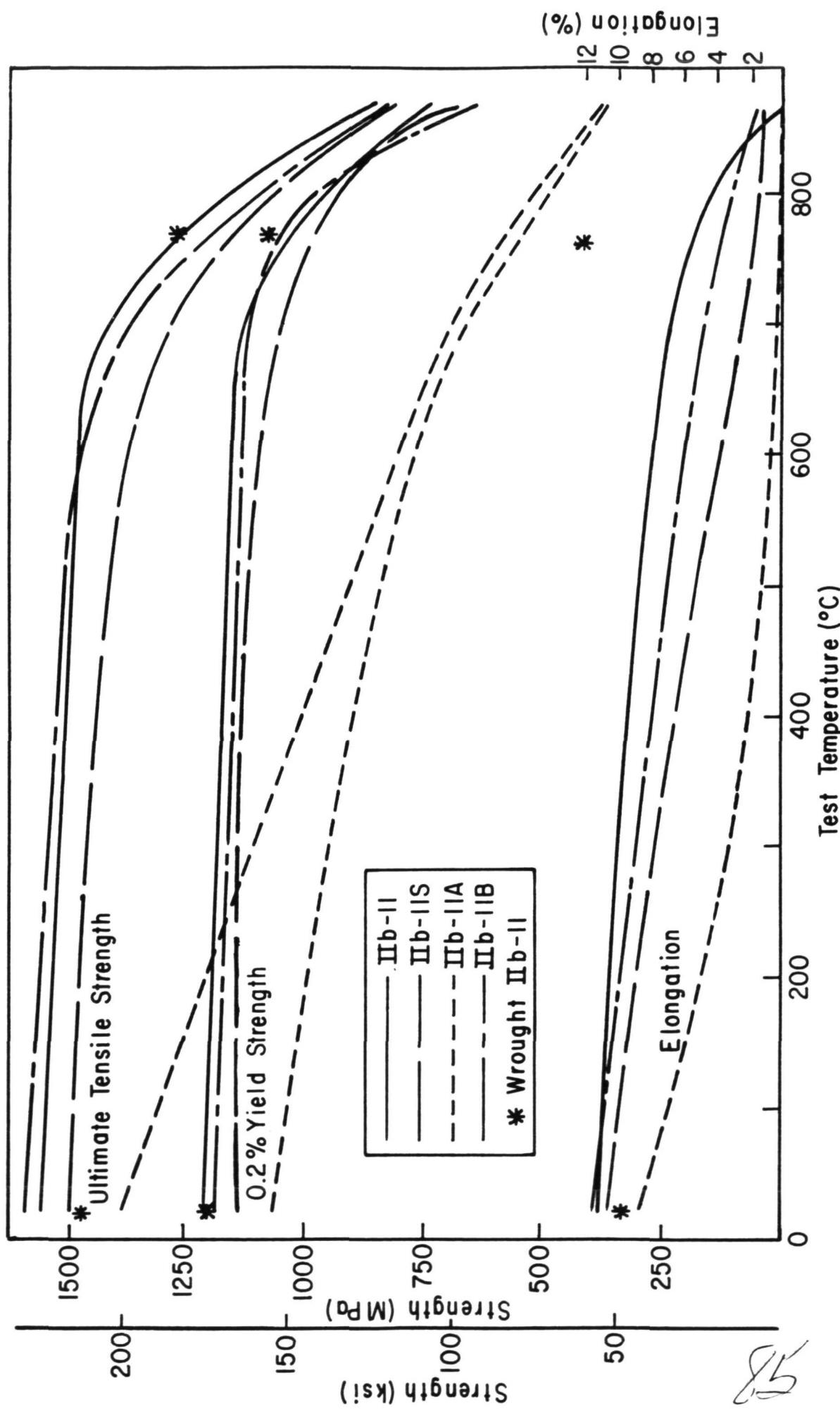
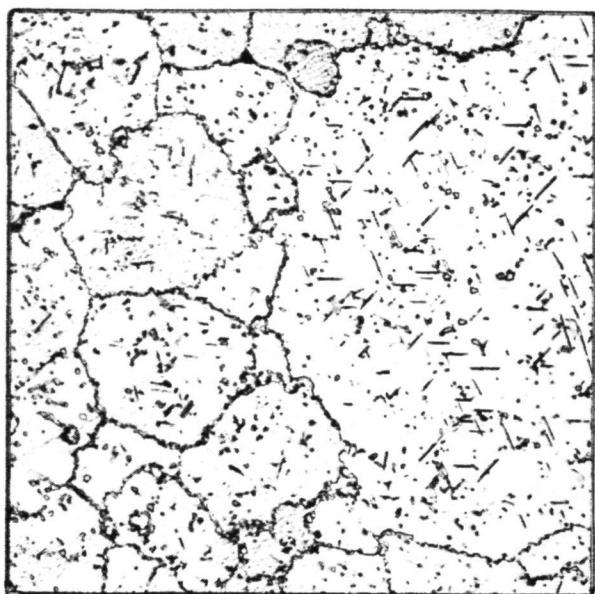
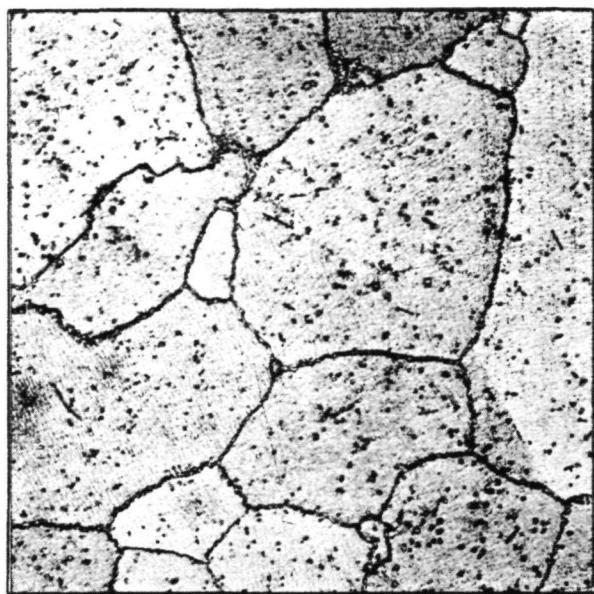


Fig. I2 : TENSILE PROPERTIES FOR TASK I – SERIES II COMPOSITIONS

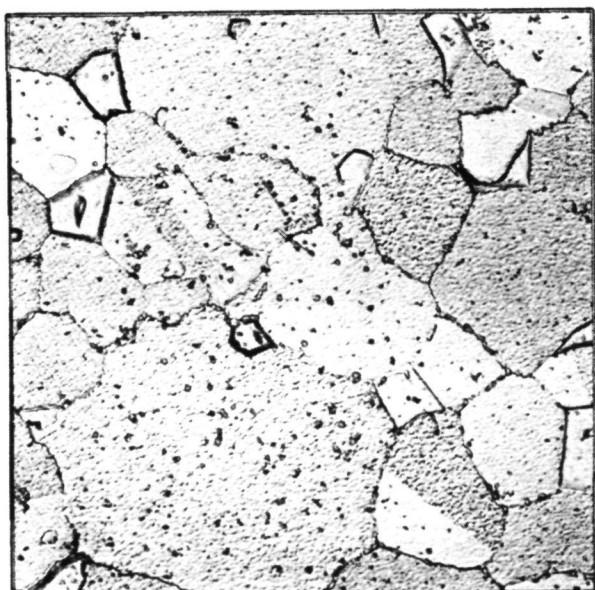
REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR



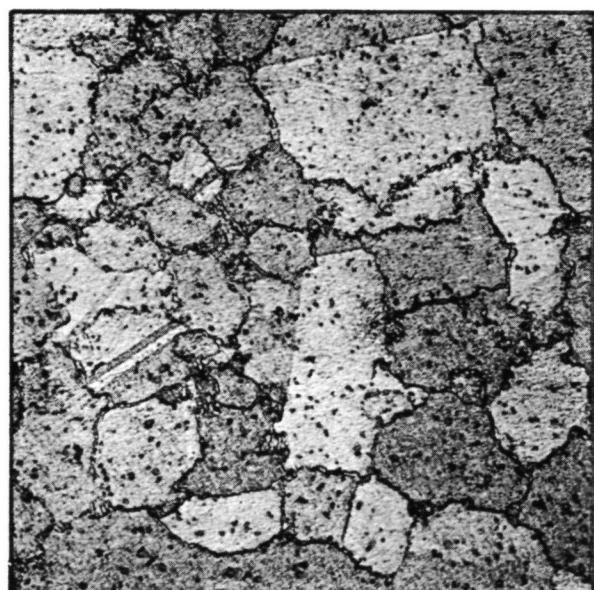
NASA IIb-II



NASA IIb-II S

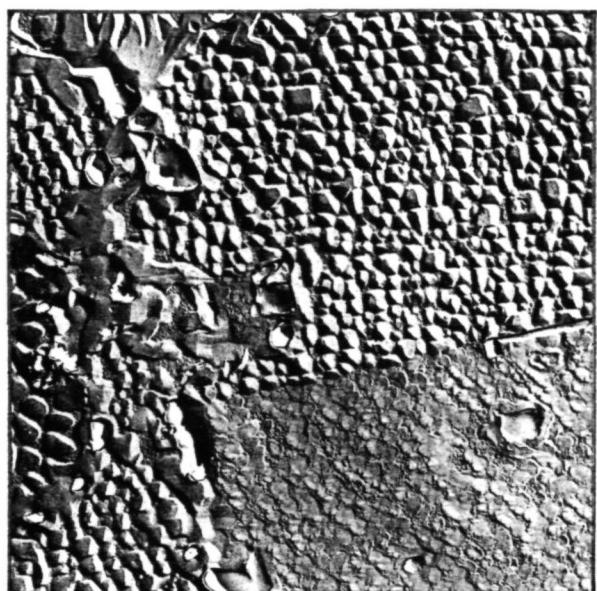


NASA IIb-II A



NASA IIb-II B

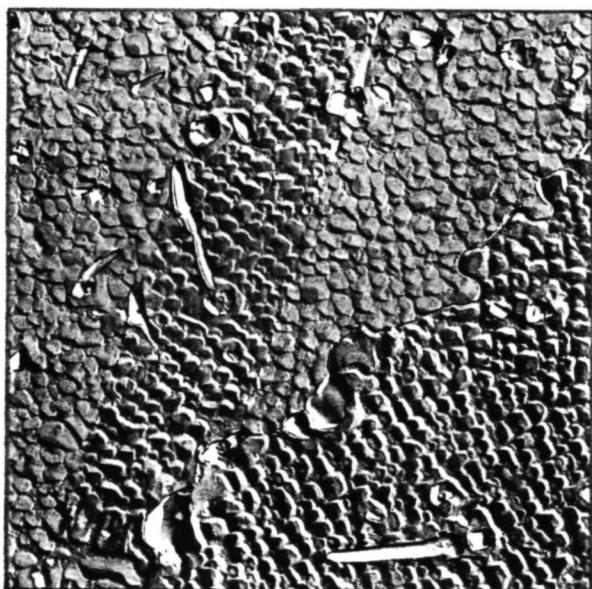
Fig. 13 : OPTICAL MICROGRAPHS ILLUSTRATING MICRO-
STRUCTURE OF FOUR TASK I - SERIES II
COMPOSITIONS AFTER EXPOSURE AT 870° C
(1600° F) FOR 1500 HOURS.



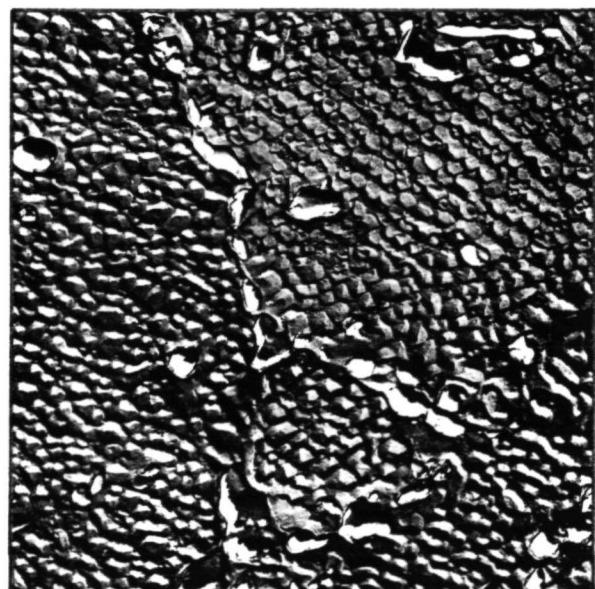
EM5374



EM5373



EM 5371

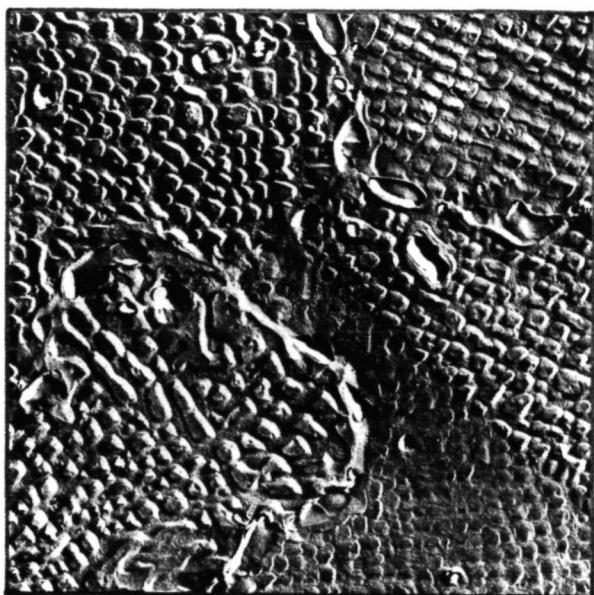


EM5370

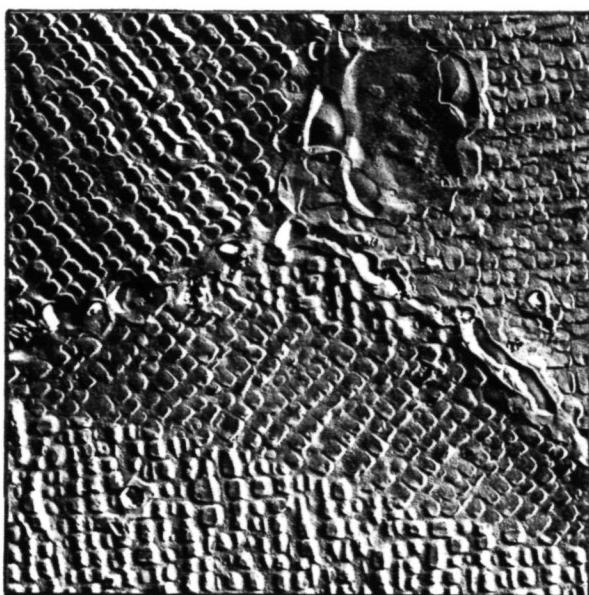
Fig. 14 : ELECTRON MICROGRAPHS OF NASA IIb-II
AFTER HEAT TREATMENT PLUS THERMAL
EXPOSURE

87

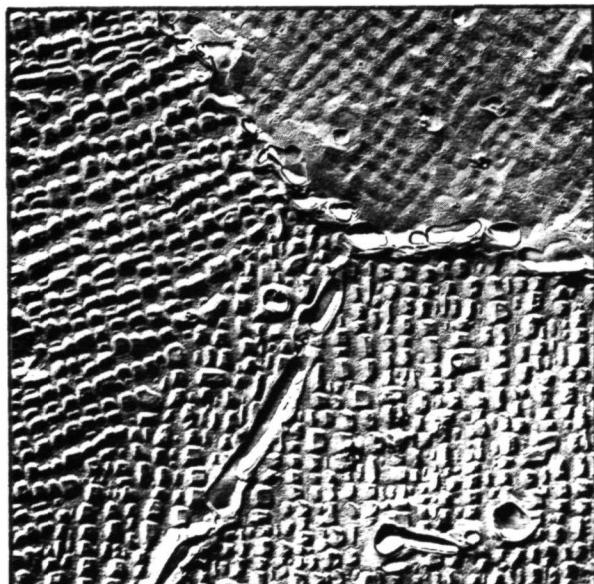
Mag. : 6000X



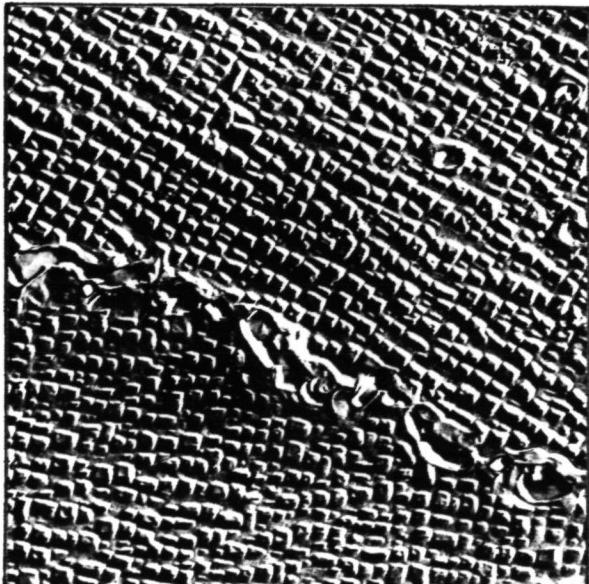
EM5385



EM5384



EM5380

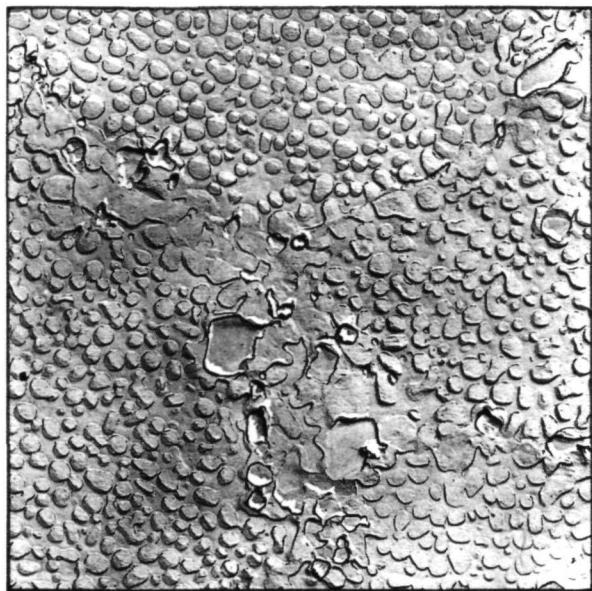


EM5381

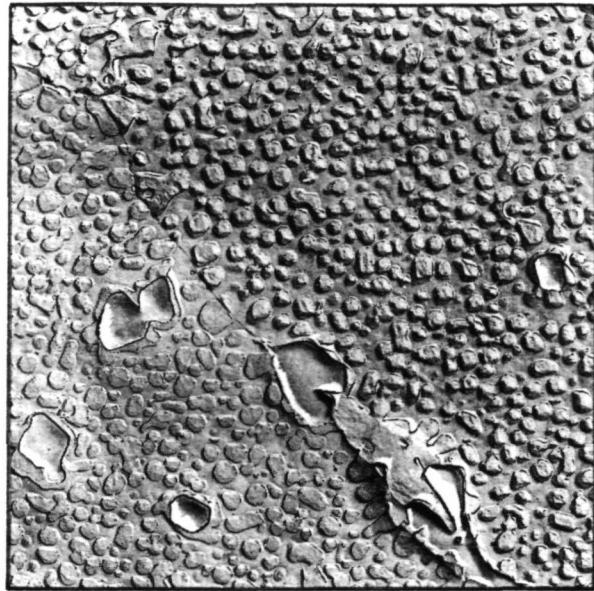
Fig. 15: ELECTRON MICROGRAPHS OF NASA IIb-IIS
AFTER HEAT TREATMENT PLUS THERMAL
EXPOSURE.

Mag. : 6000X

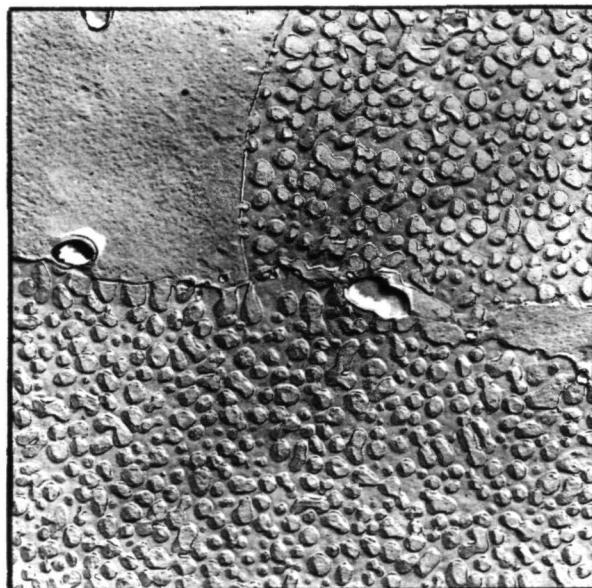
88



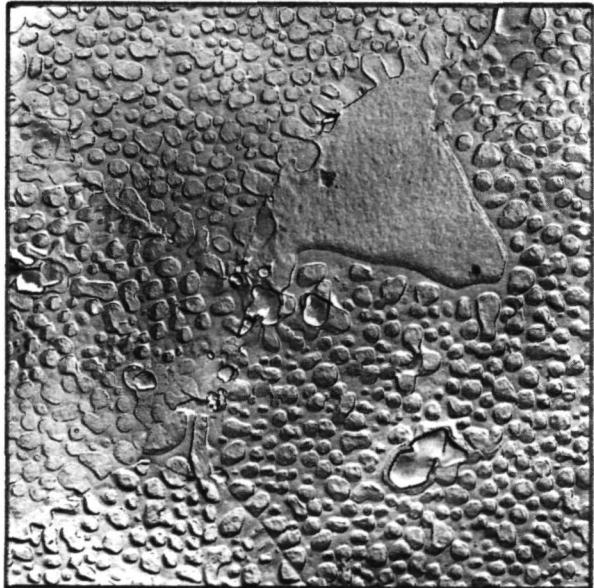
EM5400



EM5395



EM5398



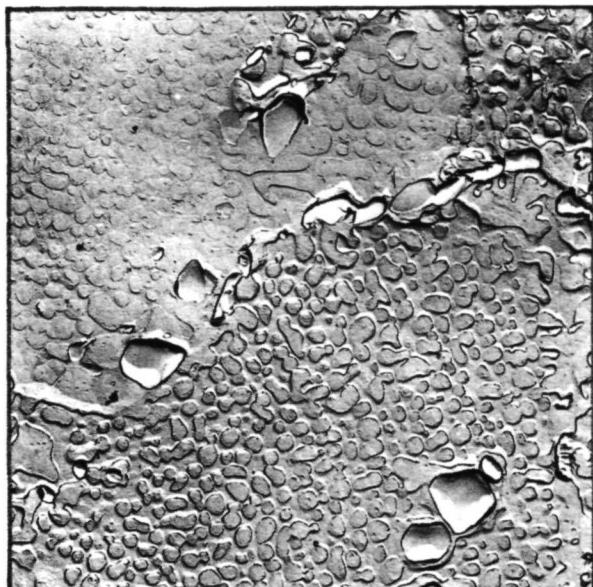
EM5399

Fig. 16 : ELECTRON MICROGRAPHS OF NASA IIb-IIA AFTER HEAT TREATMENT PLUS THERMAL EXPOSURE

Mag. : 6000X



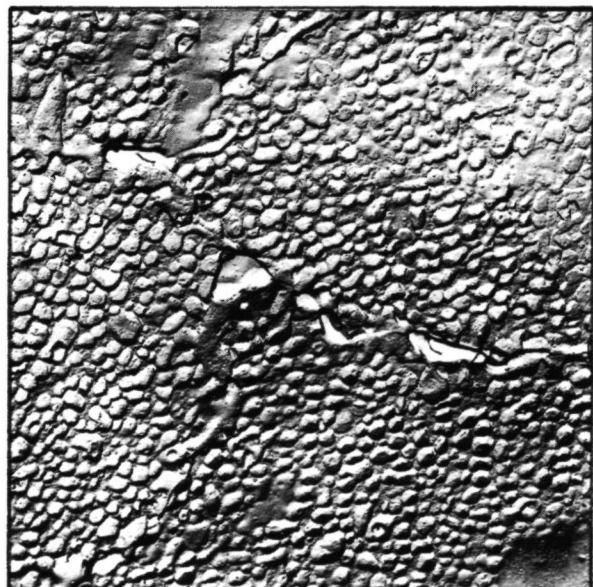
EM5393



EM5387



EM5389

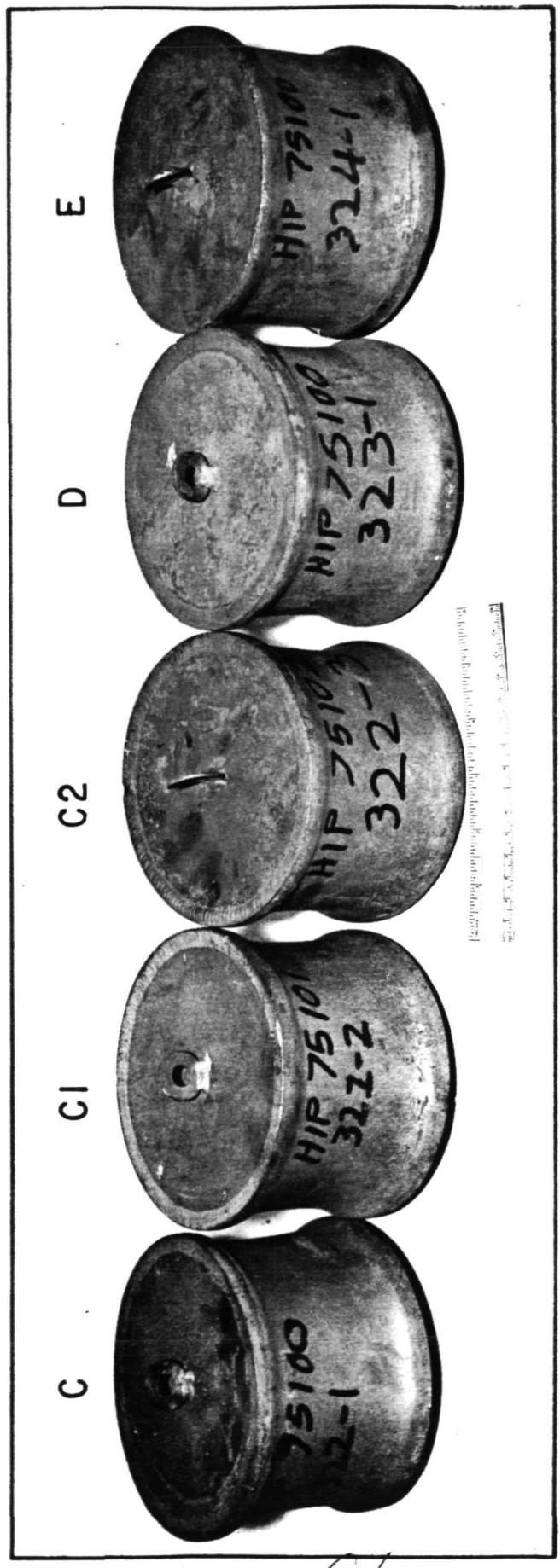


EM5392

Fig. 17: ELECTRON MICROGRAPHS OF NASA IIb-IIIB
AFTER HEAT TREATMENT PLUS THERMAL
EXPOSURE

Mag. : 6000X

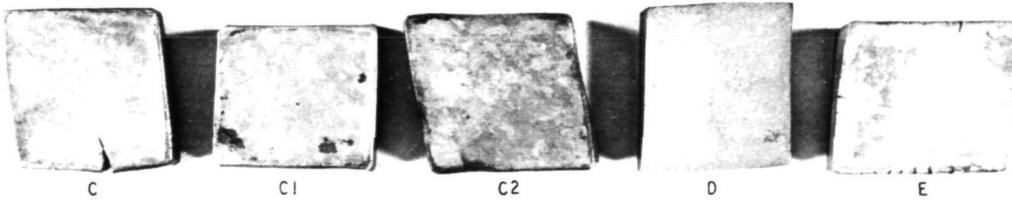
90



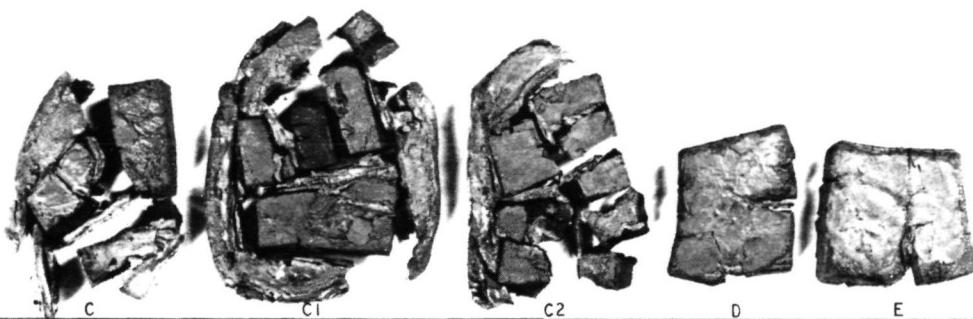
M6277

91

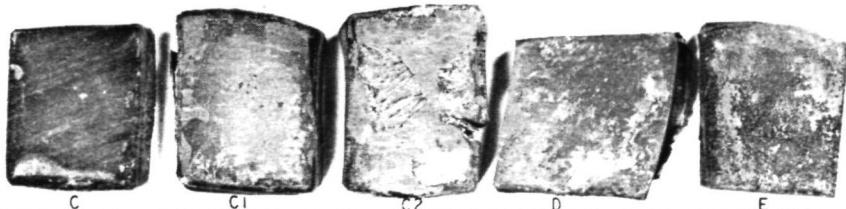
Fig. 18 : GENERAL APPEARANCE OF TASK II HOT ISOSTATICALLY
PRESSED PREFORMS



PRACTICE 1: STANDARD PASS REDUCTIONS FROM 1065° C (1950°F) WITH
SINGLE PASSES BETWEEN REHEATS.



PRACTICE 2: 1245° C (2275°F) / 2 HOURS / RAC + (1) ABOVE.



PRACTICE 3: STANDARD PASS REDUCTIONS FROM 1065° C (1950°F) WITH
DOUBLE PASSES BETWEEN REHEATS.



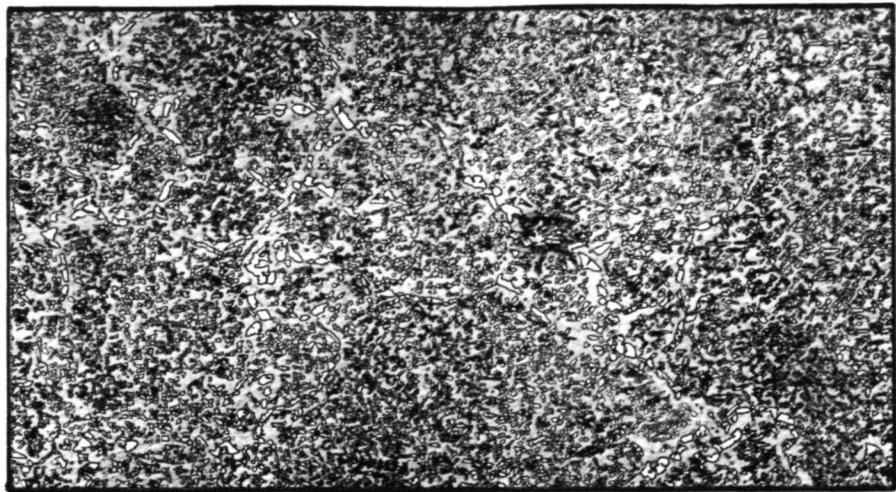
PRACTICE 4: STANDARD PASS REDUCTION FROM 1120°C (2050°F) WITH
SINGLE PASSES BETWEEN REHEATS.

Fig. 19 : EFFECT OF TASK II PRELIMINARY ROLLING PRACTICES ON
HOT WORKABILITY.

JB



FIG. 20 : GENERAL APPEARANCE OF TASK II PREFORM VARIATIONS
AFTER CROSS ROLLING.



R26484

IIb - IIC (PREFORM C)

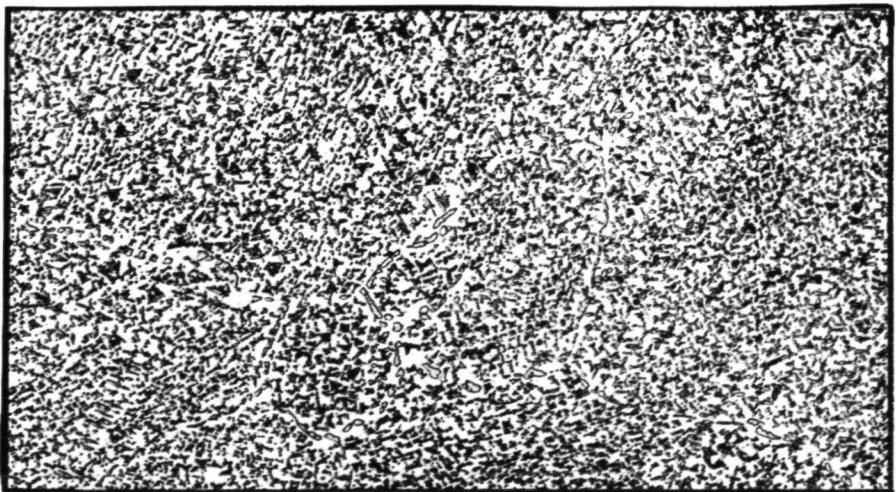
500X



R26490

IIb - IID (PREFORM D)

500X



R26492

IIb - IIE (PREFORM E)

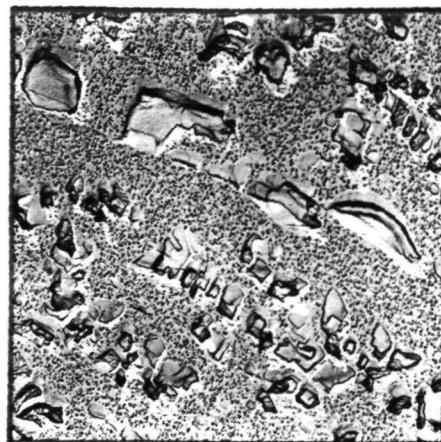
500X

FIG. 21: OPTICAL MICROGRAPHS OF THREE
TASK II COMPOSITIONS AFTER HEAT
TREATMENT.

94



EM5581



EM5582

IIb-IIc (PREFORM C)

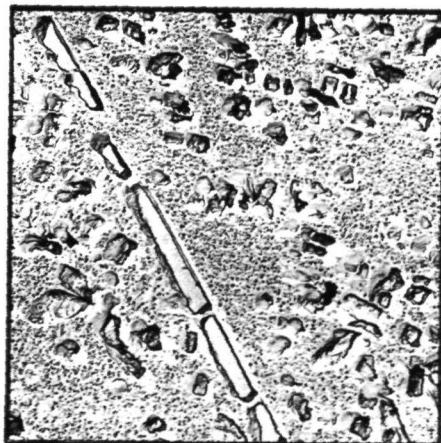


EM5600



EM5602

IIb-IId (PREFORM D)



EM5625



EM5622

IIb-IIe (PREFORM E)

FIG. 22 : ELECTRON MICROGRAPHS OF THREE TASK II COMPOSITIONS AFTER HEAT TREATMENT

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

Mag. : 6000X

95

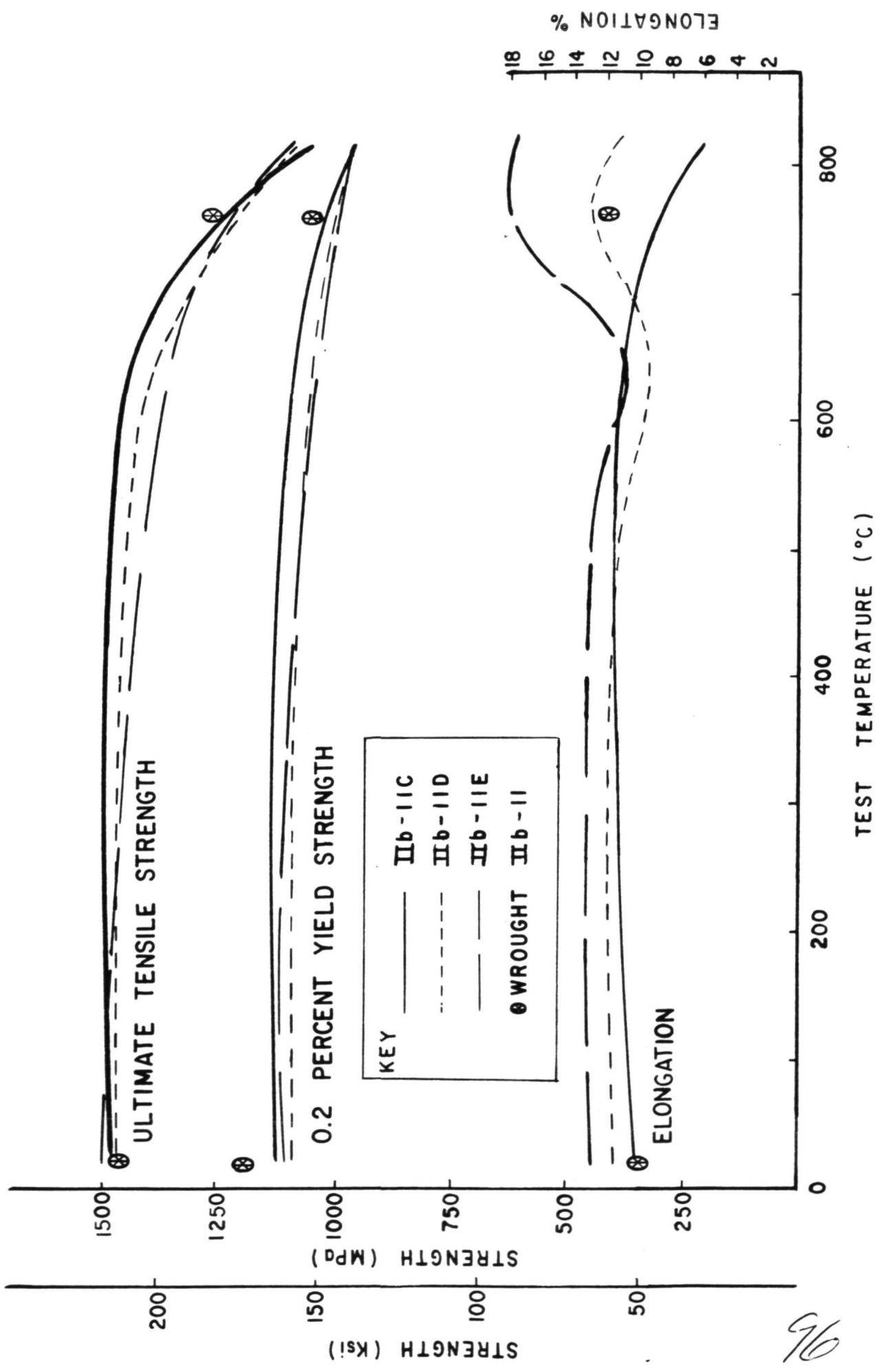
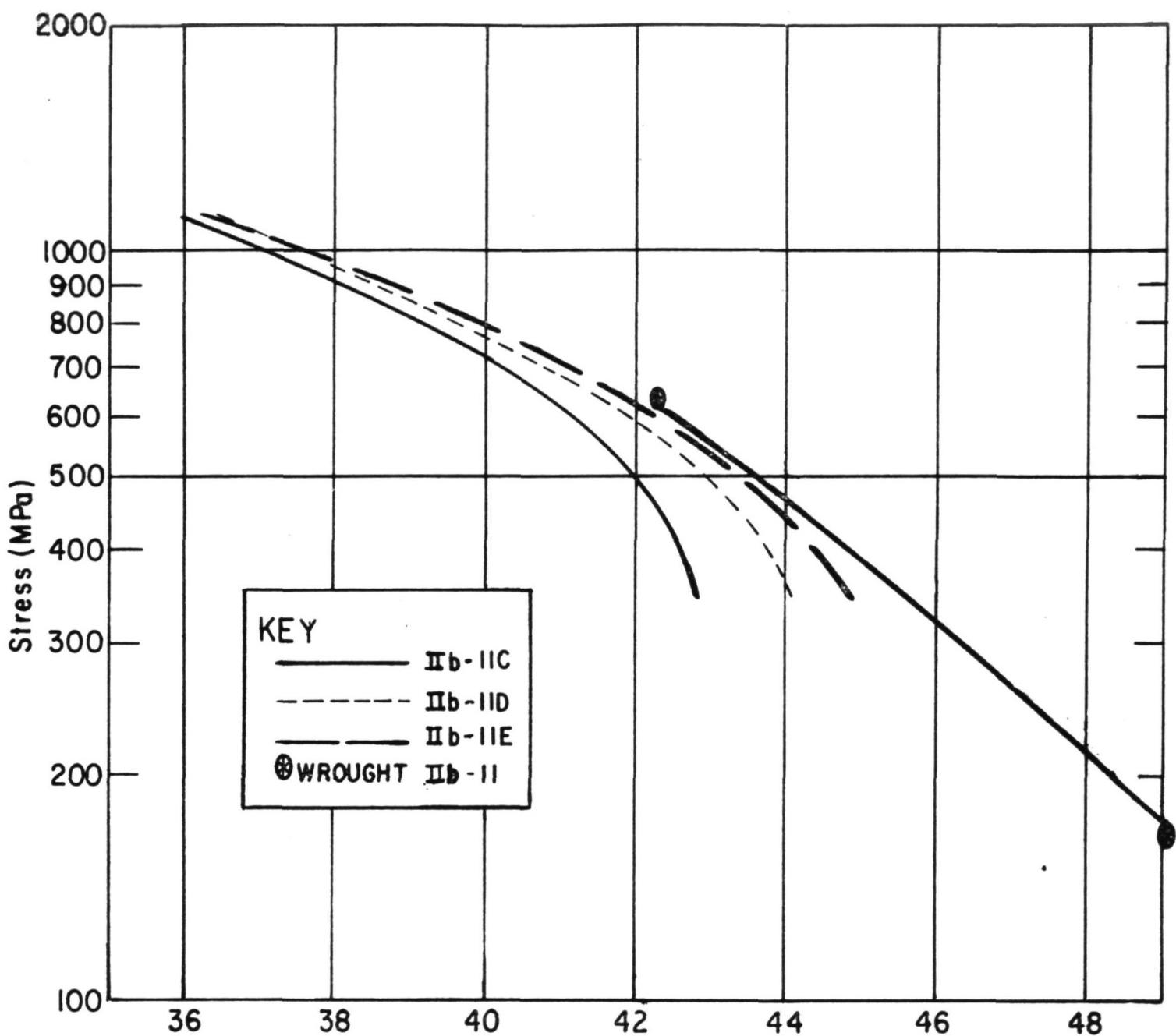


FIG. 23 : TENSILE PROPERTIES FOR TASK II COMPOSITIONS



LARSON-MILLER PARAMETER, $P = 1.8T (20 + \log t) \times 10^{-3}$
 (T IN K, t IN HOURS)

FIGURE 24 : STRESS RUPTURE PARAMETER FOR
 TASK II COMPOSITIONS

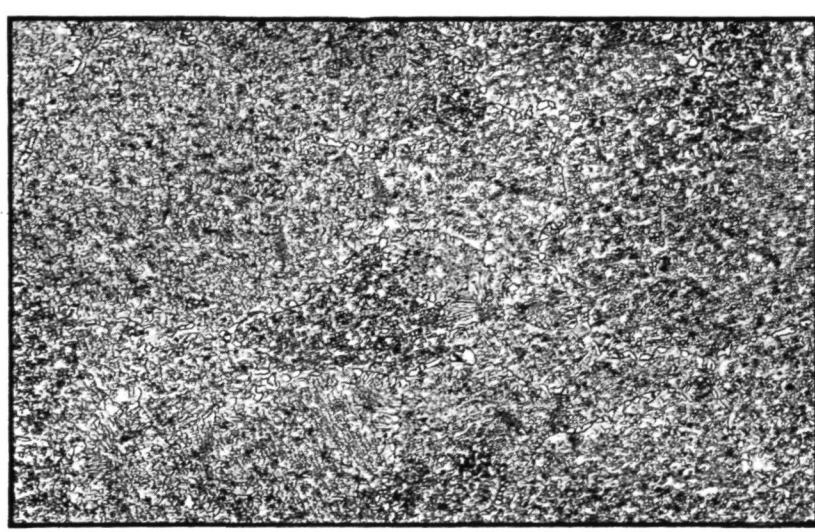
REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR



R26477

500X

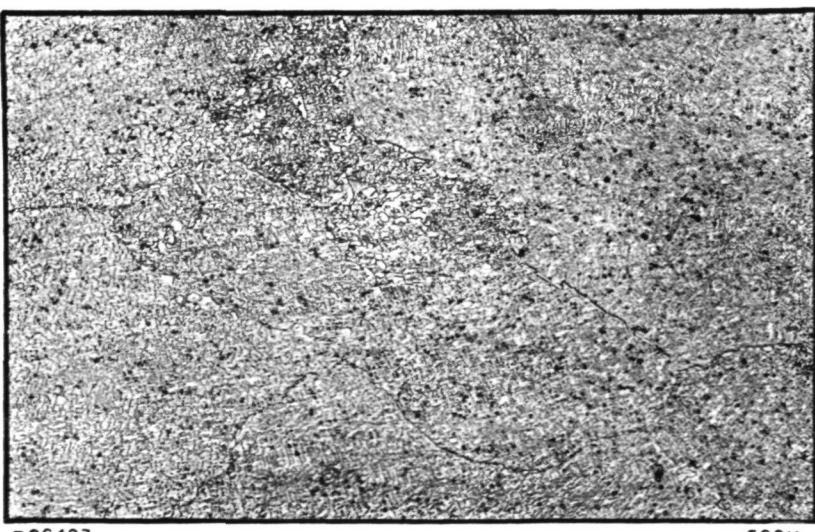
IIb - IIC (PREFORM C)



R26481

500X

IIb - IID (PREFORM D)



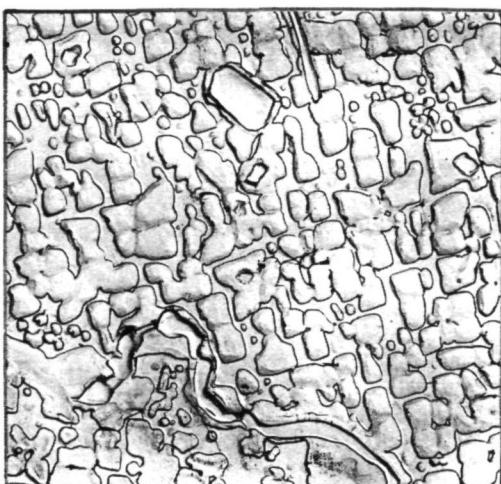
R26483

500X

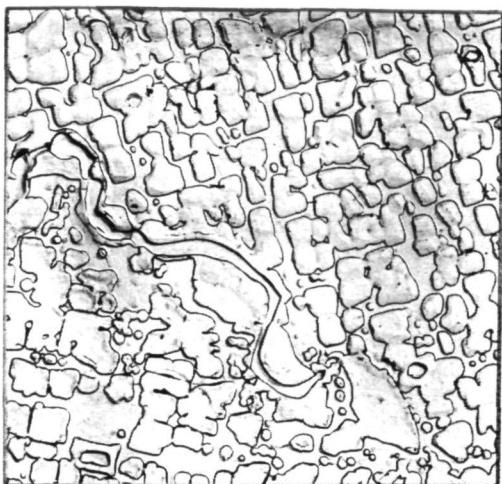
IIb - IIE (PREFORM E)

FIG. 25 : OPTICAL MICROGRAPHS OF THREE TASK II
COMPOSITIONS AFTER HEAT TREATMENT PLUS
EXPOSURE AT 870°C (1600°F) / 1500 HOURS .

98

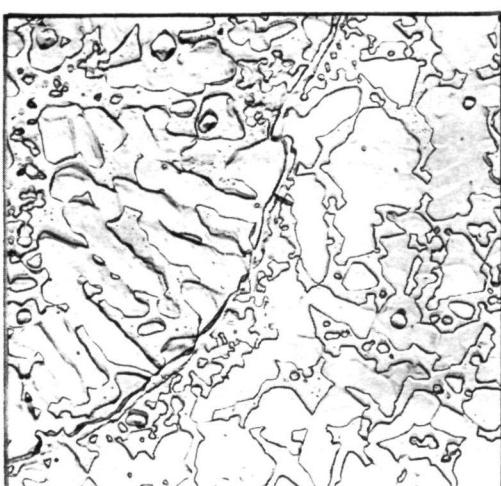


EM5599

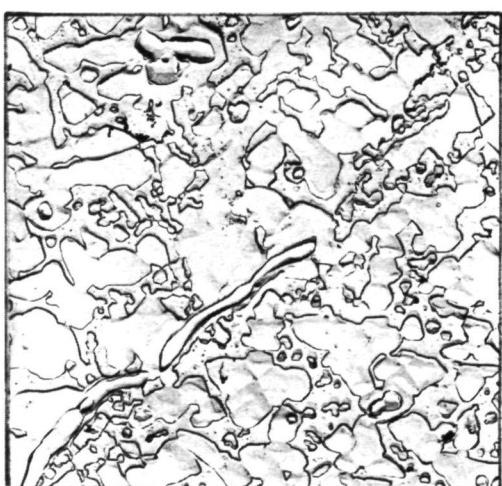


EM 5597

IIb - IIC (PREFORM C)

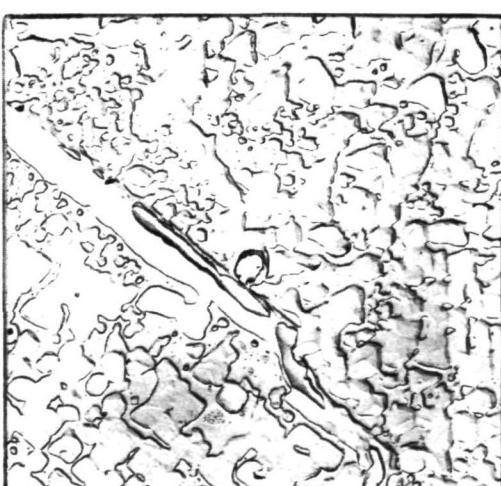


EM5606

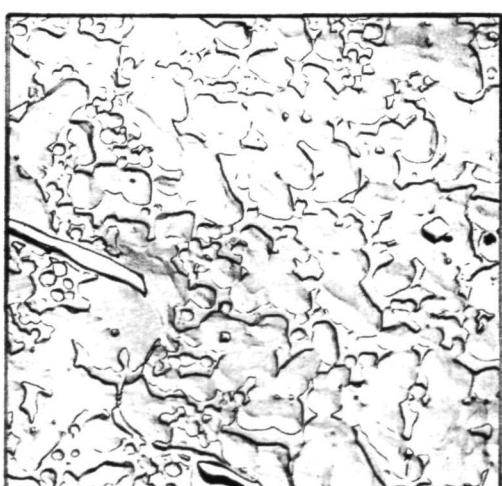


EM5605

IIb - IID (PREFORM D)



EM5610



EM5612

IIb - IIE (PREFORM E)

FIG. 26 : ELECTRON MICROGRAPHS OF THREE TASK II COMPOSITIONS AFTER HEAT TREATMENT PLUS EXPOSURE AT 870°C (1600°F) / 1500 HOURS.

Mag. : 6000X

99

DISTRIBUTION LIST FOR NASA CR-135131

NAS3-16795

(THE NUMBER IN PARENTHESES SHOWS HOW MANY COPIES
IF MORE THAN ONE ARE TO BE SENT TO AN ADDRESS.)

MR. J. ACURIO
MS 77-5
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. G.M. AULT
MS 3-5
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. C.P. BLANKENSHIP
MS 105-1
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

DR. R.L. DRESHFIELD
MS 105-1
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. J.C. FRECHE
MS 49-1
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

DR. H.R. GRAY
MS 49-3
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. R.W. HALL
MS 49-1
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. F.H. HARF (5)
MS 49-3
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. M.H. HIRSCHBERG
MS 49-1
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

M & S DIVISION FILES
MS 49-1
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

DR. R.V. MINER (5)
MS 49-3
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

DR. H.B. PROBST
MS 49-3
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. N.T. SAUNDERS
MS 105-1
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. W.J. WATERS
MS 49-3
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. J.W. WEETON
MS 49-3
NASA LEWIS RESEARCH CTR.
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

LIBRARY (2)
MS 60-3
NASA LEWIS RESEARCH CTR
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

TECHNOLOGY UTILIZATION
MS 3-19
NASA LEWIS RESEARCH CTR
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR G. C. DEUTSCH / RW
NASA HEADQUARTERS
WASHINGTON, DC
20546

CONTRACTS SECTION B
MS 500-313
NASA LEWIS RESEARCH CTR
21000 BROOKPARK ROAD
CLEVELAND, OH 44135

REPORT CONTROL OFFICE
MS 5-5
NASA LEWIS RESEARCH CTR
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MAJ. F.J. GASPERICH
AFSC LIAISON MS 501-3
NASA LEWIS RESEARCH CTR
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135

MR. J. GANGLER / RWM
NASA HEADQUARTERS
WASHINGTON, DC
20546

LIBRARY
NASA
GODDARD SPACE FLIGHT CTR
GREENBELT, MARYLAND 20771

LIBRARY
NASA
LANGLEY RESEARCH CENTER
HAMPTON, VA 23365

LIBRARY
NASA
MARSHALL SPACE FLIGHT
CENTER
AL 35812

TECHNICAL LIBRARY / JM6
NASA
JOHNSON SPACE CENTER
HOUSTON, TX 77058

LIBRARY - ACQUISITIONS
JET PROPULSION LAB.
4800 OAK GROVE DRIVE
PASADENA, CA 91102

LIBRARY
NASA
DRYDEN FLIGHT RES. CTR
P. O. BOX 272
EDWARDS, CA 93523

LIBRARY - REPORTS
MS 202-3
NASA AMES RESEARCH CENTER
MOFFETT FIELD, CA 94035

ACCESSIONING DEPT (10)
NASA SCIENTIFIC & TECHN.
INFORMATION FACILITY
BOX 8757
BALTIMORE, MD 21240

DEFENCE DOCUMENTATION CTR
CAMERON STATION
5010 DUKE STREET
ALEXANDRIA, VIRGINIA
22314

MR. M. SLAWSKY
USAF OFF SCIENTIFIC RES
PROPULSION RESEARCH DIV
WASHINGTON, DC 20525

MR. J.K. ELBAUM
AFML/LP
HEADQUARTERS
WRIGHT PATTERSON AFB,
OH 45433

MR. N. GEYER
AFML/LLP
HEADQUARTERS
WRIGHT PATTERSON AFB,
OH 45433

MR. H.A. JOHNSON
AFML/LTM
HEADQUARTERS
WRIGHT PATTERSON AFB,
OH 45433

MR. L.R. KENNARD
AFML/LTM
HEADQUARTERS
WRIGHT PATTERSON AFB.
OH 45433

MR. L.J. OBERY
AFAPL/TBD
HEADQUARTERS
WRIGHT PATTERSON AFB,
OH 45433

DR. W.H. REIMANN
AFML/LLN
HEADQUARTERS
WRIGHT PATTERSON AFB,
OH 45433

LIBRARY
ARMY MATERIALS AND
MECHANICS RESEARCH CTR.
WATERTOWN, MA 02172

MR. J. LANE
SAVDL-EU-TAPP
US ARMY AIR MOBILITY
R&D LABORATORY
FORT EUSTIS, VA 23604

DR. J.C. HURT
ARMY RESEARCH OFFICE
BOX CM
DURHAM, NC 27706

MR. T.F. KEARNS AIR-320A
NAVAL AIR SYSTEMS COMMAND
NAVY DEPARTMENT
WASHINGTON, DC 20361

MR. I. MACHLIN AIR-52031B
NAVAL AIR SYSTEMS COMMAND
NAVY DEPARTMENT
WASHINGTON, DC 20361

MR. G.J. DANEK
NAVY DEPARTMENT
NAVAL SHIP R&D CENTER
ANNAPOLIS, MARYLAND 21402

DR. S. I. FREEDMAN
ERDA
WASHINGTON, DC
20545

TECHNICAL REPORTS LIBRARY
ERDA
WASHINGTON, DC
20545

TECHNICAL REPORTS LIBRARY
OAK RIDGE NATIONAL LAB.
OAK RIDGE, TENN. 37830

MR. J.R. LANE
MATERIALS ADV. BD.
NAT. ACAD. OF SCIENCES
2101 CONSTITUTION AVE.
WASHINGTON, DC 20418

DR. L. TOPPER
OFFICE OF ENERGY POLICY
NAT. SCIENCE FOUNDATION
WASHINGTON, DC 20550

MR. F.W. BOULGER
BATTELLE MEMORIAL INST.
505 KING AVENUE
COLUMBUS, OHIO 43201

DR. G.T. HAHN
BATTELLE MEMORIAL INST.
505 KING AVENUE
COLUMBUS, OHIO 43201

MCIC
BATTELLE MEMORIAL INST.
505 KING AVENUE
COLUMBUS, OHIO 43201

DR. M.S. SELTZER
BATTELLE MEMORIAL INST.
505 KING AVENUE
COLUMBUS, OHIO 43201

PROF. L.J. EBERT
DEPT. OF MET. & MAT. SCI.
CASE - WESTERN RESERVE U.
CLEVELAND, OH 44106

DR. J.K. TIEN
HENRY KRUMB SCH. OF MINES
COLUMBIA UNIVERSITY
NEW YORK, NY 10027

LIBRARY
DENVER RESEARCH INSTITUTE
UNIVERSITY PARK
DENVER, COLORADO 80210

DR. R.I. JAFFEE
ELECTRIC POWER RESEARCH
INSTITUTE
BOX 10412
PALO ALTO, CA 94304

MR. K. KULKARNI
IIT RESEARCH INSTITUTE
10 WEST 35TH STREET
CHICAGO, ILLINOIS 60616

PROF. N.J. GRANT
DEPT. OF METALLURGY
MASS. INST. OF TECHNOLOGY
CAMBRIDGE, MA 02139

PROF. O. SHERBY
DEPT. OF MATERIALS SCI.
STANFORD UNIVERSITY
PALO ALTO, CALIF. 94305

MR. R.A. LULA
ALLEGHENY LUDLUM
STEEL CORP.
BRACKENRIDGE, PENNA.
15014

LIBRARY
AVCO SYSTEMS DIVISION
LOWELL INDUSTRIAL PARK
LOWELL, MASSACHUSETTS
01851

MR. B. GOLDBLATT
AVCO LYCOMING DIV.
550 S.MAIN STREET
STRATFORD, CT 06497

DR. D. WEBSTER
BOEING COMPANY
M.A.S.D.
SEATTLE, WA 98124

LIBRARY
CABOT CORPORATION
STELLITE DIVISION
P.O. BOX 746
KOKOMO, INDIANA 46901

MR. D.A. NAIL
CAMERON IRON WORKS, INC
P.O. BOX 1212
HOUSTON, TX 77001

MR. R. SCHWER
CANNON-MUSKEGON
MUSKEGON, MI 49443

DR. D.R. MUZYKA
CARPENTER TECHNOLOGY CORP
RES. & DEV. CENTER
P.O. BOX 662
READING, PA 19603

DR. A. ROY
METALLURGICAL RESEARCH
CHRYSLER CORP
BOX 1118
DETROIT, MI 48231

MR. H. MORROW
CLIMAX MOLYBDENUM CORP.
1, GREENWICH PLACE
GREENWICH, CT 06830

DR. D.L. SPONSELLER
CLIMAX MOLYBDENUM COMPANY
1600 HURON PARKWAY
ANN ARBOR, MICHIGAN 48106

MR. E.J. DULIS, PRESIDENT
COLT INDUSTRIES
CRUCIBLE MAT RES CTR
P.O. BOX 88
PITTSBURGH, PA 15230

MR. J. MOGUL
DIR - MATLS ENGRG
CURTISS-WRIGHT
1 PASSAIC ST
WOOD-RIDGE, NJ 07075

POWDER METALS RESEARCH
FIRTH STERLING, INC.
P.O. BOX 71
PITTSBURGH, PENNA. 15230

DR. C.E. FELTNER
FORD MOTOR COMPANY
P.O. BOX 2053
DEARBORN, MI 48123

DR. Y.P. TELANG
MATERIALS DEVELOPMENT
FORD MOTOR COMPANY
ONE PARKLANE BOULEVARD
DEARBORN, MICHIGAN 48126

DR. R.F. KIRBY
CHIEF, MATERIALS ENG.
GARRETT AIRESEARCH
402 S. 36TH STREET
PHOENIX, AR 85034

MR. J. HSIA
AEG/GED
1000 WESTERN AVENUE
LYNN, MA 01910

DR. P. MATHUR
AEG/GED
1000 WESTERN AVENUE
LYNN, MA 01910

LIBRARY
R. & D. CENTER
GENERAL ELECTRIC COMPANY
P.O. BOX 8
SCHENECTADY, N.Y. 12301

LIBRARY
ADVANCED TECHNOLOGY LAB
GENERAL ELECTRIC COMPANY
SCHENECTADY, NY 12345

MR. C.T. SIMS
GAS TURBINE PROD. DIV.
GENERAL ELECTRIC COMPANY
SCHENECTADY, N.Y. 12345

MR. G.E. WASIELEWSKI
MATERIALS & PROCESSES LAB
GENERAL ELECTRIC COMPANY
SCHENECTADY, N.Y. 12345

TECHN. INFORMATION CENTER
AEG
GENERAL ELECTRIC COMPANY
CINCINNATI, OHIO 45215

DR. R.E. ALLEN
AEG/GED
GENERAL ELECTRIC COMPANY
CINCINNATI, OHIO 45215

MR. J.L. BARTOS
AEG/GED
GENERAL ELECTRIC COMPANY
CINCINNATI, OHIO 45215

DR. J.W. SEMMEL
AEG/GED
GENERAL ELECTRIC COMPANY
CINCINNATI, OHIO 45215

MR. P.E. HAMILTON CODE W8
DETROIT DIESEL ALLISON DV
P.O. BOX 894
INDIANAPOLIS, IN 46206

DR. M. HERMAN
DETROIT DIESEL ALLISON DV
P.O. BOX 894
INDIANAPOLIS, IN 46206

MR. E.S. NICHOLS PT.8 T2B
DETROIT DIESEL ALLISON DV
P.O. BOX 894
INDIANAPOLIS, IN 46206

LIBRARY
MATERIALS SCIENCE LAB. #5
DETROIT DIESEL ALLISON
GENERAL MOTORS
INDIANAPOLIS, IN 46206

DR. E.E. REYNOLDS
TECHNICAL CENTER
GENERAL MOTORS CORP.
WARREN, MI 48090

MRS. V. SCHMIDT
GOULD LABORATORIES
GOULD INC.
540 EAST 105TH STREET
CLEVELAND, OH 44108

LIBRARY
HERCULES, INC
910 MARKET STREET
WILMINGTON, DE 19899

MR. J. WENTZELL
HOMOGENOUS METALS INC.
WEST CANADA BLVD
HERKIMER, N.Y. 13350

MR. M. GARY
HONEYWELL INC.
AEROSPACE DIVISION
2600 RIDGEWAY PARKWAY
MINNEAPOLIS, MN 55413

MR. W.H. FREEMAN
SUPERALLOY GROUP
HOWMET CORPORATION
WHITEHALL, MI 49461

DR. R. WIDMER
INDUSTR. MATLS. TECHNOL.
19 WHEELING AVENUE
WOBBURN, MA 01801

MR. J.M. SIERGIEJ
INTERMETCO
300 CONCORD ROAD
WAYLAND, MA 01778

MR. A. STETSON
SOLAR DIVISION
INTERNATIONAL HARVESTER
2200 PACIFIC HIGHWAY
SAN DIEGO, CAL. 92112

DR. R.F. DECKER
INTERNATIONAL NICKEL CO.
ONE NEW YORK PLAZA
NEW YORK, NY 10004

DR. G. BROPHY
INTERNATIONAL NICKEL CO.
MERICA RESEARCH LAB
STERLING FOREST
SUFFERN, NY 10901

MR. T. MILES
KELSEY HAYES CORPORATION
7250 WHITMORE LAKE ROAD
BRIGHTON, MI 48116

MR. R. DAYKIN
LADISH COMPANY
5481 SOUTH PACKARD AVE
CUDAHY, WISCONSIN 53110

MR. J.P. STROUP
LATROBE STEEL COMPANY
LATROBE, PA 15650

DR. J.F. RADAVICH
MICROMET LABORATORIES
202 SOUTH STREET
WEST LAFAYETTE,
INDIANA 47906

MR. G.I. FRIEDMAN
NUCLEAR METALS, INC.
229 MAIN STREET
CONCORD, MA 01742

MR. T.G. McNAMARA
ROCKWELL INTERNATIONAL
ROCKETDYNE DIVISION
6633 CANOGA AVENUE
CANOGA PARK, CA 91304

MR. N. PATON
ROCKWELL INTERNATIONAL
SCIENCE CENTER
THOUSAND OAKS, CALIFORNIA
91360

DR. J.C. WILLIAMS
ROCKWELL INTERNATIONAL
SCIENCE CENTER
THOUSAND OAKS, CALIFORNIA
91360

DR. J. PRIDGEON
SPECIAL METALS
CORPORATION
NEW HARTFORD, N.Y. 13413

MR. M. PODOB
SPECIAL METALS, INC
UTICA POWDER DIV
2310 S. INDUSTRIAL
ANN ARBOR, MI 48104

DR. R. BECK
TELEDYNE-CAE
1330 LASKEY ROAD
TOLEDO, OH 43601

MR. J.A. ALEXANDER
MATERIALS TECHNOLOGY
TRW EQUIPMENT GROUP
23555 EUCLID AVENUE
CLEVELAND, OHIO 44117

DR. C.S. KORTOVICH
MATERIALS TECHNOLOGY
TRW EQUIPMENT GROUP
23555 EUCLID AVENUE
CLEVELAND, OHIO 44117

LIBRARY
MATERIALS TECHNOLOGY
TRW EQUIPMENT GROUP
23555 EUCLID AVENUE
CLEVELAND, OH 44117

MR. L. ENGEL
TURBODYNE CORPORATION
711 ANDERSON AVE., N.
ST. CLOUD, MN 56301

DR. P.S. KOTVAL
UNION CARBIDE
RESEARCH INSTITUTE
TARRYTOWN, NY 10591

MR. M.S. WRIGHT
UNION CARBIDE CORP.
CARBON PRODUCTS DIV
P.O. BOX 6116
CLEVELAND, OH 44101

RESEARCH LIBRARY
UNITED TECHNOLOGIES CORP
400 MAIN STREET
EAST HARTFORD, CT
06108

MR. E.F. BRADLEY
PRATT & WHITNEY AIRCRAFT
UNITED TECHNOLOGIES CORP
400 MAIN STREET
EAST HARTFORD, CT 06108

MR. D.J. EVANS
PRATT & WHITNEY AIRCRAFT
UNITED TECHNOLOGIES CORP
400 MAIN STREET
EAST HARTFORD, CT 06108

MR. R.A. SPRAGUE
PRATT & WHITNEY AIRCRAFT
UNITED TECHNOLOGIES CORP
400 MAIN STREET
EAST HARTFORD, CT 06108

MR. R.L. ATHEY
PRATT & WHITNEY AIRCRAFT
UNITED TECHNOLOGIES CORP
WEST PALM BEACH,
FLORIDA 33402

LIBRARY
PRATT & WHITNEY AIRCRAFT
UNITED TECHNOLOGIES CORP
WEST PALM BEACH, FLORIDA
33402

MR. J. B. MOORE
PRATT & WHITNEY AIRCRAFT
UNITED TECHNOLOGIES CORP
WEST PALM BEACH,
FLORIDA 33402

MR. C. VAN WANDERHAM
PRATT & WHITNEY AIRCRAFT
UNITED TECHNOLOGIES CORP
WEST PALM BEACH,
FLORIDA 33402

MR. P. THOMAS
WESTINGHOUSE ELECTRIC
ASTRONUCLEAR LABORATORY
P.O. BOX 10864
PITTSBURGH, PA 15236

MR. F.J. WALL
WESTINGHOUSE ELECTRIC
STEAM DIVISION
P.O. BOX 9175
LESTER, PENNA. 19113

MR. W.P. SCHIMMEL
WILLIAMS RESEARCH CORP.
2280 W. MAPLE ROAD
WALLED LAKE, MI 48088

MR. J. COYNE
WYMAN-GORDON COMPANY
NORTH GRAFTON, MA 01436

DR. C.H. LUND
CONSULTANT
15 N. WINDSOR ROAD
ARLINGTON HEIGHTS, IL
60004